An investigation into improved thermal comfort in Kuwait schools using natural ventilation and evaporative cooling

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Abstract

Kuwait has a hot desert climate, where the energy demand for cooling dominates the country's energy requirements. Air conditioning accounts for more than 60% residential energy use and more than 85% peak consumption. Hence, the Kuwaiti government has set a target to reduce buildings energy demand by 15% by year 2030 (Cerezo *et al.*, 2017). In this context, this project presents a cooling system based on natural ventilation and evaporative cooling that is estimated to significantly reduce the cooling energy demand in school classrooms, whilst providing adequate thermal comfort and indoor air quality.

It was hypothesized that using a split system for cooling while relying on single-sided window opening for ventilation could lead to poor indoor air quality, thus adversely affecting student learning and health. The natural ventilation technology chosen is the 'wind-catcher' which provides indoor ventilation using both dynamic and stack wind pressures. The wind-catcher is modelled for a school classroom with single-sided ventilation. In this project, a total of four scenarios have been modelled: Baseline Scenario 1 – Air conditioning only; Scenario 2 – Wind-catcher only; Scenario 3 – Wind-catcher with evaporative cooling; Scenario 4 – Wind-catcher with evaporative cooling and AC for backup cooling. In each scenario, the thermal comfort, indoor quality and energy use were analysed.

After validation of the baseline scenario using field collected data, all four scenarios were simulated over a year. The results revealed that the optimal scenario was the third, wind-catcher with evaporative cooling. Based on the adaptive ASHRAE standard for thermal comfort, it is predicted to provide 98% comfortable hours in the summer, and 86% comfortable hours all year round. Additionally, in comparison with the baseline, this system is predicted to reduce energy use by 53%, as well as dramatically improving air quality (acceptable CO_2 ppm level from 20% to 90%). A computational fluid dynamics (CFD) based analysis was carried out for this scenario to assess the air velocity and air temperature distribution within the classroom in greater detail – which showed that the average air speed in the classroom is expected to be 0.78m/s.

It was noted in the study that controlling HVAC systems such as the evaporator fan and the air-conditioner using thresholds based on air temperature resulted in significant overcooling and energy wastage during the cooler periods of the year. Therefore, it is proposed in future work to use thermal comfort metrics, such as Fanger's PMV to control such HVAC components to avoid overcooling and energy wastage. Along with other recommendations, a practical demonstration of this design within a commercial, educational or hospital building in Kuwait is proposed as key future work.

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I also express gratitude to the souls of my Grandfather, Grandmother and beloved cousin Hassan.

Lastly, I would like to thank everyone that I have not mentioned who helped me successfully complete this work.

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Nomenclature

A	characteristic area	$[m^2]$
ach	air change rate	$[/h]$
C	contaminant concentration	$[ppm]$
C_d	discharge coefficient for an opening	
C_p	pressure coefficient	
Cp	specific heat capacity of air	$[J/Kg/K]$
D	diameter of duct	$[m]$
g	gravitational acceleration	$[m/s^2]$
K	temperature difference	$[K]$
K	pressure loss coefficient	
L	illuminance	$[lux]$
I	characteristic length	$[m]$
I, w, h	room length, width and height	$[m]$
v	velocity	$[m/s]$
p	mean pressure	$[Pa]$
P	aspect ratio	
Q	air flow rate	$[m^3/s]$
Q	heat flow	$[W]$
rms	root mean square	
R	reflectance of a surface	
T_a	Temperature	[°C]
T_i	Temperature of surface	[°C]
t	time	[s]
U, V, W	velocity components in x, y, z directions	$[m/s]$
V	volume of space	$[m^3]$
V_r	reference wind speed	$[m/s]$
$\in$	Effectiveness of component	
$\propto$	direction angle	[°]
θ	Incidence angle normal to the surface	[°]

Chapter 1– Introduction and background

1.1 Background

Building energy is responsible for about 40% of the global energy use, and is predicted to continue growing in the decades to come (Xing, Hewitt and Griffiths, 2011). For countries in which the use of fossil fuels dominates the production of energy, this energy use in buildings directly leads to environmental emissions, thus having a negative impact on the environment. Kuwait is such a country where the primary energy is almost solely sourced from oil and gas reserves (KISR, 2019). According to Figure 1-1, based on the current government policy and practices, fossil fuel will dominate the energy use within the country in the decades to come.

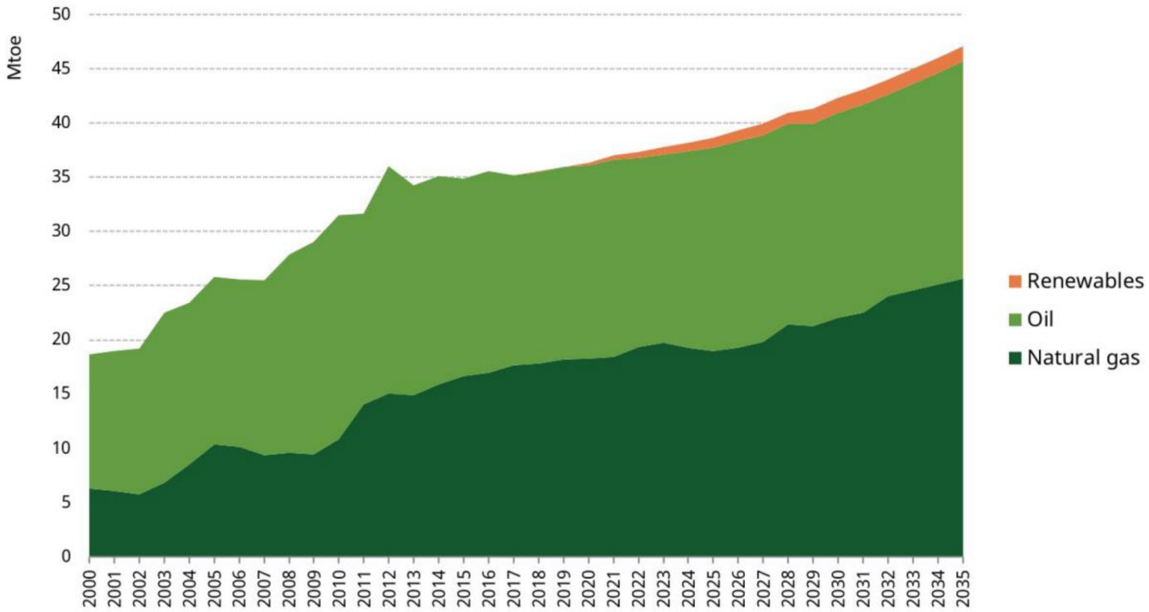


Figure 1-1: Primary energy demand project in Kuwait based on 'business and usual' practices (KISR, 2019)

Kuwait's per capita energy consumption is among the highest globally; in 20011 for instance, the country's per capita energy consumption was 13,061kWh (MEW, 2014). Kuwait's energy sector is currently characterized by highly subsidized tariff and under-pricing policy which makes it commercially unviable.

Kuwait, situated in Southwest Asia at latitude 29.369 and longitude 47.978, is hot and dry and the country experiences short winter periods and long summer periods. The summers have extreme high temperatures, as recorded and analysed by Nasrallah, Nieplova and Ramadan (2004). Figure 1-2 shows Kuwait's average monthly maximum and minimum temperatures and design temperatures indoors. Largely, air conditioning systems are used in Kuwait to provide comfortable conditions during the summer, while there is no space conditioning provided in the winter season.

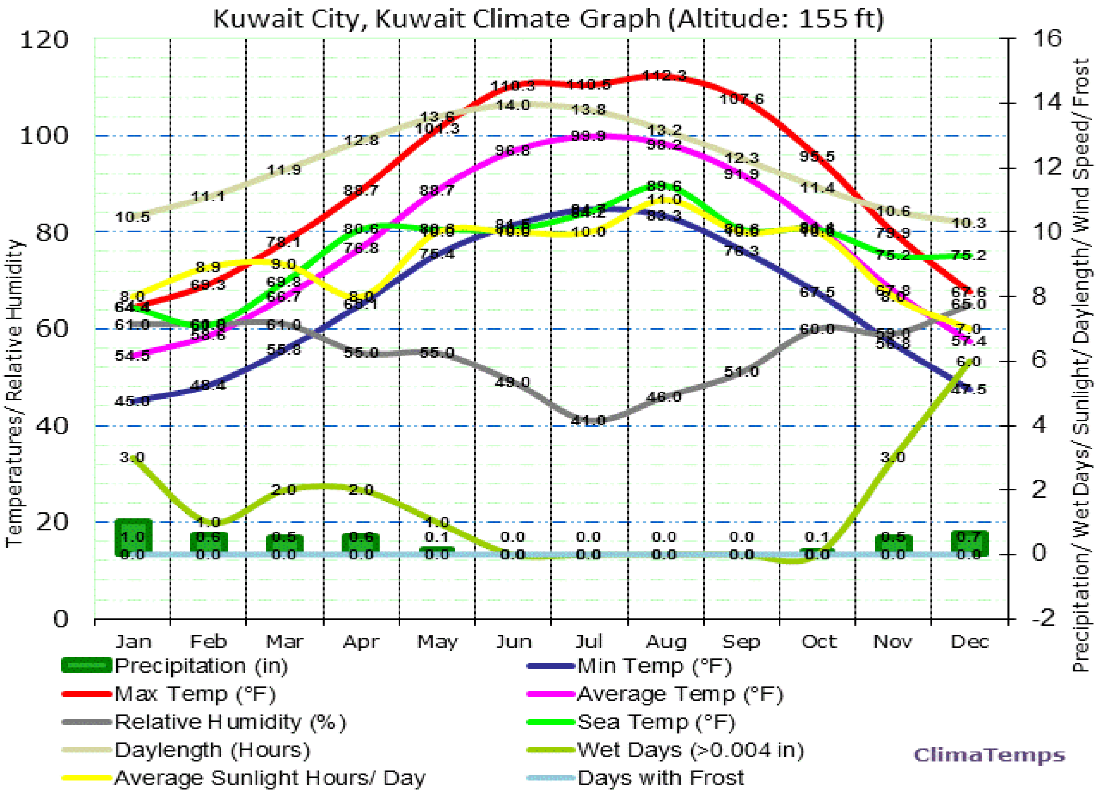


Figure 1-2 – Climate summary of Kuwait, showing the profiles of temperatures, relative humidity, precipitation, wet days, day length, wind speed and frost. Note that this data indicates a hot desert climate. (Kuwait MET, 2017)

In such a climate, cooling dominates the buildings energy demand, where air conditioning accounts for more than 60% residential energy use and more than 85% peak consumption. Current Kuwaiti governmental target for the year 2030 is to reduce the buildings energy demand by 15% (Cerezo *et al.*, 2017). Within this context, it becomes very important to develop strategies to reduce energy consumption whilst providing comfortable and healthy buildings indoor conditions. Within the buildings sector, this thesis focuses on the education sector in Kuwait. Of all the energy consumption in Kuwait, 10% - 15% alone is consumed by the Education sector, mainly in schools. The consumption each year in this sector is increasing by approximately 5% (MEW, 2014). According to (MOE 2009), Kuwait has approximately 360,000 school going students and 540 schools and averagely each classroom is occupied by approximately 45 students. (MOE 2009) also projects a 10% yearly increase in the number of Kuwait schools. Starting from the 1990s there was extensive construction and renovation of buildings in schools in Kuwait. School buildings were equipped with air conditioners to enhance human thermal comfort and quality of air in the buildings. However, the air conditioning systems in these school buildings are not directly controlled by the teachers/pupils and so this may negatively impact the students' comfort and well-being. For example, tightly air-conditioned spaces may lead to low rates of air changes, leading to poor indoor air quality due to rising CO2 levels. In case the air change rate is increased, then the air-conditioning system will consume considerably greater amount of electricity during peak summer conditions. Therefore, for the case of schools will a high occupant per meter square, in the peak summer conditions in Kuwait, even though the AC based cooling strategy may be able to provide the required thermal comfort, or perhaps even suitable air quality, but certainly it would be difficult to achieve both in an energy efficient manner. Schools utilize approximately 10% of the annual electricity produced in the country which is approximately (2.1 GWh) at an operating cost of approximately KD 60 million; additionally, it is estimated that each student consumes about 21.6 kWh (MEW, 2010).

Considering the hot, dry desert climate, there is minimal to no need for buildings heating. However, current practice in classrooms to achieve acceptable thermal comfort may compromise indoor air quality. Within recent years, issues relating to indoor human comfort and air quality have received significant attention from researchers globally. This is attributed to lifestyle changes where today people spend over 90% of their time in artificially controlled environments. This kind of lifestyle affects the health, productivity and performance of occupants, and if these environments are not properly constituted, they can have damaging aftereffects on individuals and the society at large. These negative effects include increased medical expenses and reduced productivity at work which consequently affects the economy. Widespread studies have been carried out to examine human comfort and quality of indoor air in different types of buildings in order to enhance occupants' comfort and surrounding air conditions and improve the productivity and performance of occupants. For example (Awbi, 2013) presents different natural ventilation strategies that can aid mechanical ventilation to provide superior air quality and reduced energy consumption. Within this context, this thesis focuses on thermal comfort and energy efficiency in classrooms, with the added aspect of indoor air quality focusing of CO2 concentration levels (as that is the main pollutant to adversely impact human health).

1.2 Indoor air quality issues in classrooms

It can be argued that mechanical ventilation on its own cannot remove large amounts of indoor heat gains, especially during summer when internal heat gain is a major concern. Therefore, it becomes necessary to incorporate cooling measures together with its associated costs in order to enhance human comfort indoors. Considering hot climates such as in Kuwait, it makes classrooms important indoors spaces that not only need air conditioning but also to maintain indoor air quality to prevent health issues. Often, to achieve thermal comfort whilst reducing energy use, indoor air quality (IAQ) is compromised. Therefore, reduction of energy use in conjunction with IAQ is important, which is how this issue is tackled in this thesis.

Reports have shown that indoor air quality problems in school buildings can arise as a result of implementing energy saving measures in buildings (Clements *et al.*, 2008). This is mainly achieved due to a reduced ventilation rate that leads to a lower thermal load, but also a lack of fresh air – as indoor air quality is linked to recycled air in the occupied indoor space. Such an energy saving strategy may be detrimental to the children's health and educational performance. Furthermore, children inhale higher air volumes with respect to body weights than adults making them more vulnerable to various environmental toxins compared to adults (Landrigan, 1998; Faustman *et al.,* 2000). Classrooms with poor 'indoor air quality' (IAQ) can negatively affect the children's learning process and their overall performance. Mendell and Heath (2005) are of the view that the effects of this on health could last a lifetime. Several research studies have been conducted in schools worldwide to investigate issues relating to IAQ (Moseley-Braun *et al.*, 1995). The field study by Myhrvold and Olesen (1997) investigated the concentration of students in 35 classrooms in Norway by measuring the students' reaction times under various rates of ventilation. The results of the study showed that by lowering the rate of ventilation per person from 12 L/s to 4L/s, students' reaction times reduced by 5.4%. In Japan, it was established that by raising the rate of ventilation from 0.6L/s to 6L/s, the students' performance was enhanced by 5.5% (Wargocki, P. and Wyon, 2006). Furthermore, Wargocki (2007) and Wargocki *et al.*, (2008) conducted a study to investigate how the rate of ventilation affects the performance of ten year old school going children carrying out similar tasks. From the research it was established that by raising the rate of ventilation up to 10L/s from 5L/s, there was a 15% improvement in the school's work performance as well as a conspicuous improvement in the learning and performance of individual children. In another study conducted in 2 classrooms in the UK, it was established that by raising the ventilation rate from between 0.3L/s and 5L/s to between 13L/s and 16L/s, there was a 7% improvement in the rate at which students worked out subtraction and addition math tests (Zain, Taib and Baki, 2007).

1.3 Natural ventilation for healthy comfort:

Natural ventilation designs allow improved air speeds to improve the perception of thermal comfort whilst improving indoor air quality. Additionally, natural ventilation are passive designs and have the potential to reduce the overall energy demand of the building in which it is deployed. In particular, wind catchers use passive stack ventilation principles and have been used in Middle East countries for over 3,000 years (Bahadori, 1994). This study highlighted that wind catcher systems are beneficial because they use passive cooling techniques to naturally cool buildings, through buoyancy or wind effect and traditionally due to evaporative effects. Wind catchers also have some disadvantages; for instance, dust, sand, tiny birds, insects and other airborne pollution get into the building. Additionally, the wind catcher system can only store a small amount of cool air. In a number of studies, wind catchers were found to be ineffective in regions with low prevailing wind speeds while conventional wind catcher designs that employ evaporative cooling had limited application (Karakatsanis, Bahadori and Vickery, 1986). While wind catchers may have great potential as a natural ventilation design for cooling in classrooms, their drawbacks must be carefully considered before they can be beneficial. Additionally, wind-catchers alone may not be able to deliver the required thermal comfort considering the extreme summer temperatures in Kuwait. Therefore, evaporative cooling is sometimes employed as an assistive technology as part of the wind-catchers to provide the necessary thermal comfort in hot summer conditions. Therefore, this project considers wind catchers together with evaporative cooling as the technology/design to be considered, presented in Chapter 4 (Modelling and validation). Next, the primary aim of this research and the necessary objectives to achieve the aim are listed below.

1.4 Aim and Objectives

In the context of improved natural ventilation designs for classrooms in Kuwait as discussed in the previous section, the primary aim of this work is presented as follows:

"To develop a natural ventilation strategy for classrooms in the hot and dry climate of Kuwait, to provide satisfactory thermal comfort and improved indoor air quality in an energy efficient manner".

The objectives to achieve this aim are as follows:

1. To review literature on thermal comfort studies in classrooms in general, and in hot and dry climates.
2. To review natural ventilation systems and designs suitable for application within the Kuwaiti classrooms context.
3. Collect building details and field data on temperatures in summer from a school in Kuwait.
4. To create and validate model using the field measurements.
5. To develop alternative energy efficient designs based on natural ventilation and compare their performance through modelling.
6. To document and summarise the developments and suggest future directions of research.

1.5 Outline of the thesis

Chapter 1 provided background to the energy used in the buildings sector in Kuwait. The importance of considering ventilation strategies in conjunction with indoor air quality in classrooms has been highlighted. Therefore, the motivation to carry out research on ventilation systems design in classrooms has been provided.

Chapter 2 provides a detailed literature review on several topics that provide the theoretical background to the systems developed in this project. First, the concept of thermal comfort is detailed, with especially highlighting the impact of indoor air velocity on thermal comfort indicators in hot climates. As the four scenarios defined in this project involve mechanical cooling as well as natural ventilation, the appropriate thermal comfort models and standards have been described (ASHRAE PMV and the ASHRAE adaptive model). Wind-catchers were especially focused on as they appeared to be a promising technology to provide thermal comfort in classrooms without compromising indoor air quality whilst reducing the cooling energy demand. Based on the review of state-of-the-art literature, knowledge gaps are identified and highlighted based on which four scenarios for modelling and investigation have been defined (Chapter 4).

Chapter 3 provides an overview of the different research methods available. A detailed description of the research methodology employed in this project has been provided. This includes the quantitative analysis approach, software tools used for estimating thermal comfort, indoor air quality and energy use, along with a detailed section on field data collection to be used in validation of the created computer models.

Chapter 4 provides detail on the modelling of the four scenarios, namely, Scenario 1 – Air conditioning only (Baseline**)**, Scenario 2 – Wind-catcher only, Scenario 3 – Wind-catcher with evaporative cooling, Scenario 4 – Wind-catcher with evaporative cooling and AC for backup cooling. The baseline scenario has been validated against real world field collected data and presented in this chapter – that forms the basis of the projected estimations.

Chapter 5 provides the results for the four scenarios defined in terms of (i) thermal comfort (ii) indoor air quality (iii) energy use (iv) water use (v) detailed air velocity and temperature profile using CFD analysis.

Based on the results of simulations presented in Chapter 5, **Chapter 6** presents an analysis of the work along with developing discussions to provide deeper insights into the generated results. Finally, **Chapter 7** provides conclusions provides directions to future research within this specific topic area.

Chapter 2 – Literature Review

This chapter provides the background that underpins the research presented in this thesis. Through the review of literature, the knowledge gap to be addressed in this work is highlighted. First, the concept of thermal comfort is described, generally as well as specifically within the Geographical context of classrooms analysis in Kuwait. Based on ample evidence from literature, the concept of increasing air speeds to expand the temperature range in which satisfactory thermal comfort is experienced in hot climates is detailed. As this provides motivation for elevated air speeds in hot climates, the principles of ventilation in buildings, and the designs/strategies that accomplish this purpose are detailed. As natural ventilation is a method that allows energy efficiency, increased air velocity and improved indoor air quality, additional detail is provided regarding natural ventilation. As the design presented in this thesis utilizes direct evaporative cooling and 'wind-catchers', both are described. A historical background and exemplar applications of the 'wind-catcher' systems are also provided as it is an important part of the proposed design in this thesis. From the reviewed literature, knowledge gaps are identified and highlighted in the final conclusions section of this chapter. This leads to a clearly specified research question for which a research methodology is defined and presented in Chapter 3 afterwards. The figure below succinctly shows what concepts have been reviewed to arrive at the research question that is ultimately addressed in this doctoral thesis.

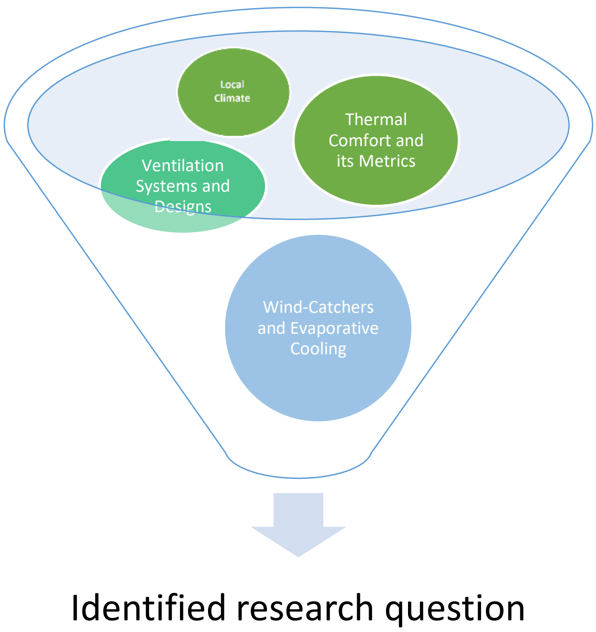


Figure 2-1 - Background review to identify the research question to be addressed in this thesis

To conduct the literature review, technical reports, textbooks, web pages, conference proceeding, and scientific journal articles were reviewed. For this purpose, different scientific databases were utilized. Namely, ScienceDirect, Google Scholar, Web of Science. The key words used were buildings energy, natural ventilation, mixed mode ventilation, air conditioning, thermal comfort, indoor air quality, hot climates, wind-catcher, evaporative cooler, energy efficiency, thermal comfort standards and building regulations. These lists of words were combined in various ways using the Boolean operators 'AND' and 'OR'. As a result, 1000+ abstracts were reviewed from which 400+ full text paper was read. This resulted in the selection of 110 technical report, websites, conference proceedings and journal articles referenced in this document. What follows is a review of the topics the answer the following questions (i) what is thermal comfort and how can we measure it? (ii) What principles govern air flow in natural ventilation? (iii) What is the wind-catcher and how has been employed around the world so far? (iv) How does elevated air flow (possibly from wind-catchers) impact the perception of thermal comfort?

2.1 Thermal comfort

Buildings space is conditioned in order to make them comfortable for the occupants. This is done by controlling the indoor air parameters such as temperature and humidity. However, the way occupants perceive comfort varies between individuals, and therefore becomes a challenging objective to provide conditions in which all occupants would be 'comfortable'. According to ASHREA 55 2004 (Turner *et al.*, 2008), thermal comfort is defined as "Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation". However, among a group of people, this perception of comfort can be different. According to Wang et. al., (2018), these difference can be classified into (i) Inter-individual difference: the variance in comfort between people (ii) Intra-individual difference: the variance in comfort for one person, in the same conditions on difference occasions. Thermal comfort in humans is influenced by six major variables namely air temperature, air velocity, mean radiant temperature and relative humidity which are physical variable as well as behaviourally controlled variables namely clothing insulation and rate of metabolism (Fountain and Arens, 1994). These are briefly explained as below.

2.1.1 Environmental Variables that impact thermal comfort

According to the thermal comfort standard, ASHREA 55 2017 (ANSI/ASHRAE, 2017), **air temperature** t_a describes the temperature of air adjacent to the skin of an individual and it is characteristic of the surrounding.

Heat is exchanged between bodies through radiation, convection and conduction. According to ASHRAE 55 2004 (Turner *et al.*, 2008), **mean radiant temperature (** $\bar{t_r}$ **)** is the uniform surface temperature of a hypothetical black enclosure inside which the amount of heat a subject would exchange through radiation would be the same as the amount that would be exchanged in a real non-uniform surrounding.

Air Velocity (v_a**)** is the flow of air against or across a body. Air velocity has both direction and magnitude, can vary over time and space. The mean air velocity (v_a), refers to the average instantaneous speed of air over a given time interval (ASHRAE 55 2004), and is used in practical applications to take air velocity into account.

Humidity is the amount of water vapour present in air called humidity, and is usually expressed in terms of **relative humidity** $\emptyset$, which is defined as the amount of water vapour contained in air expressed as a percentage of the amount that would saturate the air at the same pressure and temperature.

2.1.2 Personal Parameters that affect thermal comfort

Heat Production due to metabolism can greatly affect the perception of thermal comfort for an individual. Metabolism refers to the process by which the human body converts the chemical energy from food into thermal energy and mechanical work measured in Wm^{-2}or met. **Metabolic rate** can be determined for example through the calorimetric process or approximated using standard tables such as from ASHRAE 55 2004 (Turner *et al.*, 2008).

However, in determining the metabolic rates for special groups of individuals for example children, the elderly, people with disabilities, pregnant women among others there is need to make appropriate corrections to the data in the standard tables (Parsons, 2003)

Clothing provides insulation to the wearer thus changing the perception of environmental conditions. This is calculated using the garments adorned, where each garment is assigned a ‘CLO’ value, this is representative of its clothing insulation.

Due to the above-mentioned factors that can influence thermal comfort, different comfort indices and have been defined and remains a subject of research. What follows is a brief description of the typical thermal comfort indicators, designed to quantify the satisfaction among a group of occupants.

2.1.3 Indices or indicators for thermal comfort

Thermal comfort indices describe a thermal surrounding and how it affects occupants. This is a much-debated issue in research, which has led to several studies and models suggesting and recommending various thermal comfort indices. Among these, the most relevant are listed below followed by their brief description.

1. Wet globe temperature
2. Operative temperature
3. Fanger's PMV model
4. Adaptive comfort model

2.1.4 Wet globe temperature

These indices are directly derived from the measurement of the environmental factors described in the preceding section. **WBGT (Wet Bulb Globe Temperature) Index** is a heat stress index which shows the effects thermal environmental conditions have on an occupant's body. An individual can show considerable intolerable heat strain that can cause illness or even death. The WBGT index employs the Dukes-Dobos relationship to combine the black globe temperature t_g , dry-bulb temperature t_{db} and naturally ventilated wet-bulb temperature t_{nwb} into one value (Henschel, 1980). The wet bulb thermometer can be used to measure humidity, however, as Budd (2008) point out, this index has many limitations, mainly owing to the many measurements required to utilize it. A simpler index, the **WGT (Wet Globe Temperature)** is a method of describing a thermal surrounding and its effect on humans, defined initially by Botsford (1971). A wetted globe thermometer referred to as a Bots-ball is used to measure temperature. The Bots-ball thermometer has a black copper sphere with a diameter of 65mm with a wet black cloth covering – to measuring the required temperature variables. A limitation of the WGT index is that it is suitable for use in moderate to warm climates. (Onkapam *et al*. 1980) showed the relation between WBGT index and WGT index, and stated that in moderate to warm thermal surroundings, the WBGT index can be determined more simply with satisfactory accuracy using WGT.

Direct indices are best for measurement and approximation of thermal environmental conditions. They are quick and reasonably accurate measures of the thermal comfort with focus being on the shortcomings of each of the indices. However, their results depend on data being collected, which is therefore a pre-condition for these methods to be used.

2.1.5 Operative temperature

Operative temperature (t_o) was suggested by Winslow *et al*. (1937). According to the ASHRAE 55 standard, the operative temperature t_o is defined as the mean of the ambient temperature t_a and mean radiant temperature $\bar{t}_r$ each weighted according to their corresponding heat transfer coefficients as follows:

t_o = A t_a + (1-A) $\bar{t}_r$

Where, A donates the coefficient dependent on the relative air speed, available from the table below.

Table 2-1: Values of A coefficient due to relative air velocity (ASHRAE 55, 2004).

Relative air speed, v_r (m/s)	**< 0.2**	**0.2 - 0.6**	**0.6 - 1.0**
Coefficient, A	0.5	0.6	0.7

According to (Gagge *et al*. 1971) operative temperature can be taken as the direct measurement of environmental heat stress on an occupant - a result of reasonable heat loss only.

2.1.6 Fanger model

In 1970, Fanger proposed a thermal comfort model that predicts the average thermal sensation and dissatisfaction amount a group of occupants in a thermal environment (ISO, 2005). The Fanger model has two comfort indices, the predicted mean vote (PMV) and the predicted percentage of dissatisfied occupants (PPD). The PMV is basically the average vote of a group of occupants, who cast their vote per hour based on the ASHRAE seven-point scale Table 2-2. A full description of Fanger’s thermal comfort model and the parameter on which it depends, to provide a PMV value is provided in (Turner *et al.*, 2008). While the PMV is a prediction, if the occupant votes are recorded experimentally, then it is referred to as Actual Mean Vote (AMV), also recorded using the same scale.

Table 2-2: ASHREA seven point thermal sensation scale (Turner et al.*, 2008).*

Sensation	Description
3	Hot
2	Warm
1	Slightly Warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

While the PMV is a measure of thermal sensation, the PPD is a further derivative indicator based on the PMV that allows the analyst to quantify the prediction of percentage of dissatisfied people in the thermal zone. This was also done through empirical data, followed by fitting a regression model to the curve (please see the figure below).

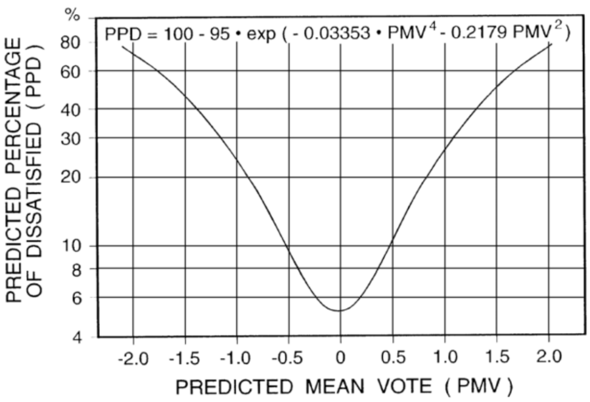


Figure 2-2 - PPD based on PMV - using empirical data. Note the mathematical relationship to describe the curve at the top of the chart (Turner *et al.*, 2008)

In the following decades, this model, which is simply referred to as the PMV/PPD model, was then incorporated into several international standards such as ANSI/ASHREA standard 55 in 1992 and the Chinese GB/T standard 18049 in 2000. The main limitation of this model is that it is based on empirical data from experiments that uses a very slow changing thermal environment, which can be approximated as steady state conditions. Such conditions may be developed in buildings using mechanical cooling systems, however in buildings with natural ventilation systems, the fluctuations are significant which impact the accuracy of the Fanger's model predictions. This has been demonstrated by several studies, for example De Dear et. al.,

(2001) showed that in buildings without mechanical cooling systems, Fanger's model overestimated the occupants dissatisfaction in both cold and warm seasons. Another limitation of the Fanger's model is that it considers the occupants as plain 'receptors', and not interactive occupants that may change their behaviour according the thermal environment. De Dear et. al., (2001) show that occupants may physiologically adapt to their thermal environment, a point that the Fanger Model simply does not take into account.

Humphrey's conducted a review literature (2002), that verified this feedback from occupants in varied thermal environments. Essentially, satisfactory thermal comfort had been recorded for occupants in a much broader range rather than stating that only a PMV=0 correlated with a satisfactory indoor thermal environment.

2.1.7 Adaptive comfort models

As a result, adaptive models were developed. Adaptive thermal comfort models take into account this feedback from the occupant, which essentially adapts according to the outdoor environmental conditions. The expected indoor thermal comfort temperature that adapts to the outdoor dry bulb temperature is calculated as follows,

$$T_c = aT_o + \ b$$

Where

T_c is the expected indoor thermal comfort temperature, T_o is the outdoor reference temperature, a is the slope of the function, proportional to the degree of adaptation, b is the y-intercept

This equation is established using empirical data for different geographic locations, climates and cultural contexts. Therefore, the constants 'a' and 'b', depend on empirical data gathered within a specific context, and related to the climatic conditions and cultural background etc. The outdoor reference temperature was redefined relatively recently in 2013, in the ANSI/ASHREA 55 2017 standard (ANSI/ASHRAE, 2017), and terms it as '*prevailing mean outdoor air temperature*' which is calculated as follows:

$$Prevailing\ mean\ outdoor\ air\ temperature = \frac{Monthly\ mean\ Max.outdoor\ temperature + Montly\ mean\ Min.outdoor\ temperature}{2}$$

Within Kuwait, the above equation can be used to calculate the variation in prevailing mean outdoor air temperature. This is important as it would provide information on whether the

ASHRAE standard is applicable for these weather conditions. Figure 2-3 shows the average monthly high and low temperatures in Kuwait City, Kuwait. Using this data for one previous year, the prevailing mean outdoor air temperature equates to a range of 14°C to 38.7°C. Therefore, any adaptive model used should have a prevailing mean temperature that covers this range. In case of the ASHRAE adaptive model, the upper limit for the prevailing outdoor temperature limit is 33.5°C. Clearly, the summer months in Kuwait City lie above this range and is indeed a knowledge gap in the area of thermal comfort for hot climates.

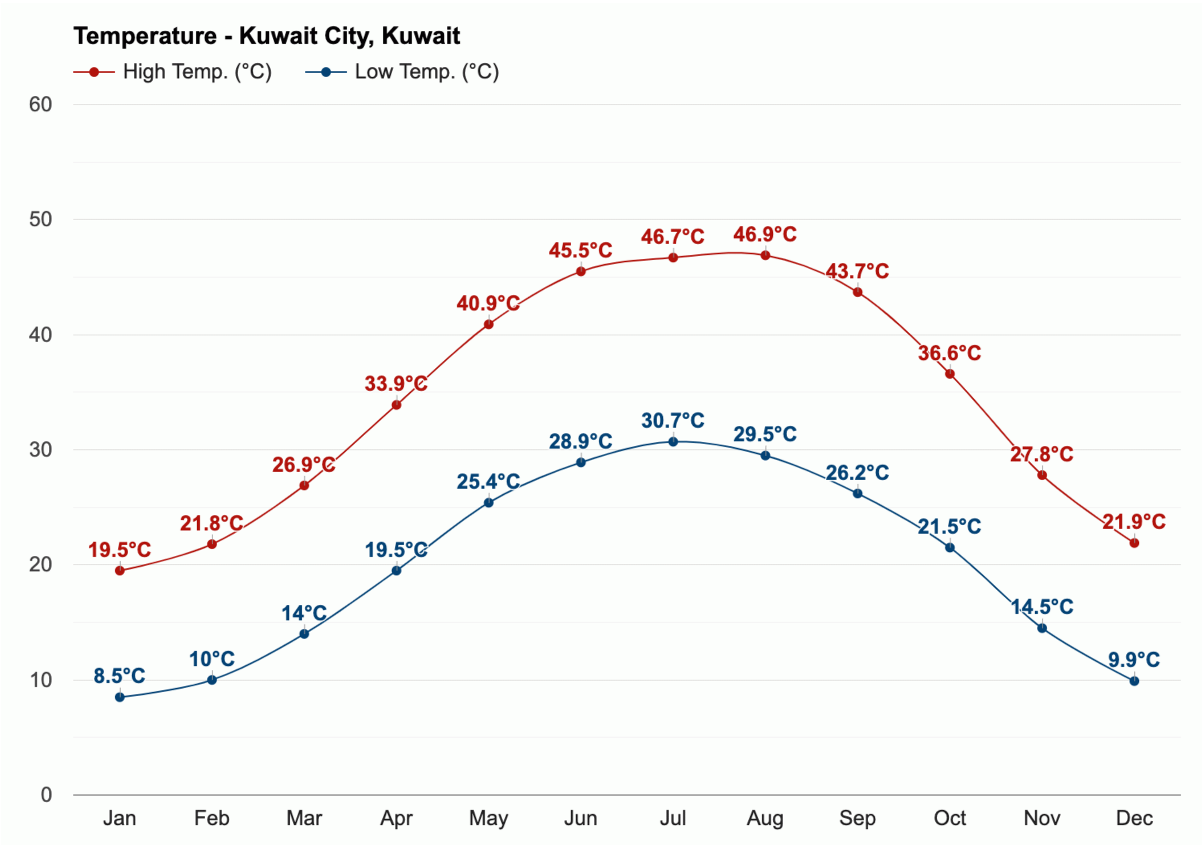


Figure 2-3 - Outdoor monthly max and low temperature for Kuwait City, Kuwait (Atlas, 2020)

2.1.8 Comparison of models

Carlucci et. al., (2018), presents a state of the art review of thermal comfort indices, with the objective of identifying the sources of uncertainty around adaptive thermal comfort models. The paper analysed the differences between thermal comfort standards across the spectrum, namely the ASHREA standard 55, the European EN 15251, the Dutch ISSO 74 and the Chinese GB/T 50785. As evident from the brief review in the preceding paragraphs, a range of thermal comfort indices were developed by various researchers to incorporate the effect of the varying climatic conditions and are classified as adaptive thermal comfort indices. The development of these indices and their standardization over time is displayed in Figure 2-4,

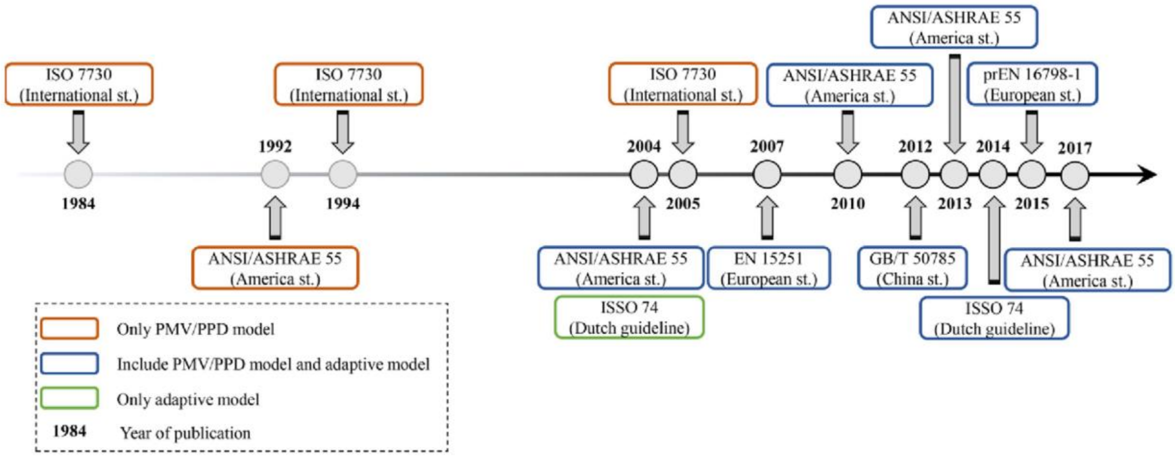


Figure 2-4 - Chronology and composition of the different thermal comfort standards worldwide (Carlucci et al., 2018)

The above standards were grouped into representative climates based on representative cities as shown in the following table (Carlucci et al., 2018). From Table 2-3 that resulted from this recent review article and the 33.5°C limitation on the '*prevalent mean monthly outdoor temperature' in* the ASHRAE adaptive model, it is clear that to date, a thermal comfort standard that is designed for very hot summers, as is the case for desert areas such as Kuwait, is missing, and is possibly a knowledge gap that can be explored.

Table 2-3 - Climate characterization of selected cities (Carlucci et al., 2018)

Climate characterization of the selected cities.

City name	Köppen-Geiger classification	Subtype	Description
Amsterdam	Marine west coast climate	*Cfb*	Mild and temperate climate, although occasionally quite cool, influenced by its proximity to the North Sea to the west, with prevailing westerly winds and a noteworthy rainfall throughout the year
Beijing	Humid continental climate	*Dwa*	Monsoon-influenced cold and temperate climate with a colder, windier, drier winter that reflects the influence of the Siberian anticyclone, and a higher humidity in the summer due to the East Asian monsoon
Palermo	Hot-summer Mediterranean climate	*Csa*	Warm climate with a moderate seasonality characterized by hot and dry summers dominated by the subtropical high-pressure system and winters with moderate temperatures and changeable, rainy weather due to the polar front
San Francisco	Warm-summer Mediterranean climate	*Csb*	Mild year-round climate with little seasonal temperature swings with moist and mild winters and dry summers that reflect the influence of the cool currents of the Pacific Ocean
Shanghai	Humid subtropical climate	*Cfa*	Monsoon-influenced mild and humid climate with a chilly and dry winter due to the influence of northwesterly winds from Siberia and a hot and wet summer due to the East Asian monsoon

2.1.9 Thermal comfort in educational buildings

Zomorodian et. al., (2016) review thermal comfort indicators specifically for educational buildings. It should be noted that instead of a 20% threshold for dissatisfaction, in educational buildings, this threshold is lower at 10% PPD (ASHRAE 55 2017), thus imposing stricter thermal comfort requirements. After reviewing thermal comfort standards across the spectrum, the paper concludes that ISO 7730, EN15251 and the ASHREA standard 55 were inappropriate for application to classroom environments. The article also concluded that there is a need for spatial and temporal comfort metrics specially designed for classrooms. As already highlighted, there is a limitation in applying currently available thermal comfort standards in hot desert climate, but moreover these findings from Zomorodian et. al., (2016) suggests that even if such models were valid for application in such climates, they would still not be well suited to the analysis of classroom environments in this climate.

While a number of limitations of the currently present and standardized thermal comfort models for application in the Kuwaiti context have been identified, the objective in this thesis is not to develop a novel thermal comfort model for classrooms in Kuwait. Rather, the currently available thermal comfort models will be used to assess the performance of novel ventilation systems design for more efficient cooling and improved indoor air quality in classrooms in Kuwait. Nonetheless, through this process, the limitations of the currently widely used thermal comfort models such as Fanger's PMV and PPD, and the ASHREA 55 adaptive thermal comfort model, should become evident and present an avenue for future research. The next section provides a review of thermal comfort studies in the Kuwait climate and then in classrooms, to further highlight the above identified knowledge gap in Thermal comfort models for classrooms within the Kuwaiti context.

2.1.10 Thermal Comfort and Indoor air quality in classrooms and public spaces

Jarrar (1979) carried out a study of thermal comfort in Kuwait Institute of Scientific research (KISR) offices and determined ideal indoor thermal conditions. The research involved 30 male and female participants exposed to varying air temperatures and relative air humidity and constant air speed and the mean radiant temperature. The study established differences in how the participants adjusted to the surrounding environmental conditions based on gender and nationality. Standard tables were used to estimate the participants' metabolic rate (1.2 met for light office activity, and clothing insulation = 0.8 clo). The study established different mean comfort temperatures among the different participants; 25.2℃ for Kuwaiti males, 23.9℃ for non-Kuwaiti males and 25.0℃ for all females irrespective of their nationality. The researchers attributed the difference in the mean comfort temperature between Kuwaiti and non-Kuwaiti (European, North African and Asian) males to environment acclimatization and dressing code.

Al-Mumin (2004) carried out field experiments to investigate how applicable PMV standards are in the evaluation of thermal comfort in ten government offices with air conditioning systems. The researchers used the ASHRAE 55 standard tables (Turner *et al.*, 2011) to approximate the insulation of the occupants' clothes and their rates of metabolism. The researcher used approximation for several Kuwaiti traditional attires that do not feature in the standard tables. The researchers compared the results they obtained from their study with various comfort indices to establish the most practicable comfort index as well as the most suitable temperature range that is comfortable for occupants of government offices in Kuwait. This study established that PMV values ranging from -0.5 to 0 were comfortable for the people living in Kuwait for subjects with a neutral temperature of 24℃ (Al-Rashidi, Loveday and Al-Mutawa, 2009). The study established that the Kuwaiti people preferred temperatures that were 1℃ less than the neutral temperature of bodies (in this study they preferred 23℃. Which means they prefer being slightly cold).

Relatively recently (Al-Ajmi, Loveday and Hanby, 2006) carried out a study to investigate thermal comfort and indoor conditions during the summers of 2007 and 2006. The researchers conducted their study in 25 residential building and the study involved 111 participants wearing traditional indoor attire with a mean insulation of 0.9 clo – corresponding to the native local culture, in the summer season. The researchers used thermal manikins used to measure the mean insulation value of the traditional clothing. The subjects' metabolic rates were obtained from standard tables and were given by 1.2 met for inactivity. The subjects' neutral temperature according to their actual mean vote or AMV was 25.2℃, and 23.3℃ for the predicted mean vote or PMV. To the author's knowledge, the studies discussed above are the only thermal comfort analyses conducted in Kuwait till date, with all of them either using adult participants or metabolic rates derived from adult's data. It is clear that more investigation is required within the context of Kuwait and thermal comfort, to better understand buildings design and technologies that could deliver thermal comfort within this geographical and social context.

Al-Rashidi, Loveday and Al-Mutawa (2009) conducted a review on thermal comfort in classrooms worldwide, summarizing the advances up to 2009 in Table 2-4, where the references in column 1 are provided in (Al-Rashidi, Loveday and Al-Mutawa, 2009). In the studies conducted in Kuwait, classrooms were considered, however the metabolic rates were estimated based on ASHRAE tables. This is not a reasonable assumption as these metabolic rates are based on data from adults, and therefore may not be applicable to children aged as young as 11 years as reported in the study.

For the reviewed literature, it is clear that a knowledge gap exists in the design and analysis of natural ventilation systems to deliver thermal comfort for children in classroom environment within Kuwait, and it is an objective of this thesis to provide advancement in this area.

In addition to thermal comfort, for the specific case of classrooms in the Kuwaiti climate, an associated issue of indoor air quality must be considered. Generally, schools in Kuwait are designed for mechanical or natural ventilation and don't need heating due to hot climate. In hot climatic regions where a large number of students share classrooms, the thermal or internal environment in classrooms is often poor and this affects learning particularly in big classrooms (MEW, 2014). It is hence imperative to study classroom ventilation conditions and determine effective ways to enhance the ventilation systems in classrooms.

Kuwait's energy code (MEW/R6 2010), adapts the ASHRAE standard 62 2004 (Damiano *et al.*, 2006), that stipulates ventilation requirements for various types of structures and indoor spaces. This standard recommends 7.5 L/s or 15 ft^3/min as the minimum rate of ventilation for each occupant in a classroom building having an occupancy density of 33 individuals per 90 square meters or 1000 square feet and ceiling of height 3 meters or 10 feet. According to the ASHRAE standard, a standard sized classroom for approximately 30 students would need air to be exchanged at the rate of 3 air change per hour (ACH). The Ministry of Electricity and Water recommends that classrooms in Kuwait should have an air exchange rate of 0.5 ACH for purposes of energy saving, (MEW/R6 2010). As a greater air exchange rate is desirable within the context of indoor air quality, which also can lead to increased air movement, the impact of increased air movement within the building space on thermal comfort is now reviewed.

Table 2-4 - Thermal comfort World Wide Studies in classrooms (Al-Rashidi, Loveday and Al-Mutawa, 2009).

Researcher & Published Year	Study Location	Climatic Region	Subject's Ages (years)	Average clothing insulation value (clo)	Clothing insulation calculation method	Metabolic Rate (MET)	Metabolic Rate calculation method	Classrooms Ventilation Type*	Neutral Temperature t_n (°C)
Auliciems (1972)	Reading, UK	Temperate maritime	11-16	N/A	N/A	N/A	N/A	NV	15.2
Humphreys (1977)	UK	Temperate maritime	7-9	1	Estimated	1.2	Estimated	NV	24
Kwok (1998)	Hawaii, USA	Tropical	15-17	0.42	Estimated	1.2	Estimated	NV & A/C	26.8 in NV 27.4 in A/C
Xavier and Lamberts (2000)	Florianopolis –Santa Catarina, Brazil	Tropical	15-17	0.61	Estimated	1.2	Estimated	NV	23.1
Ben Hussein *et al.* (2001)	Malaysia	Tropical	Adults	0.50	Estimated	1.2	Estimated	A/C	23-24.5
Cheong *et al.* (2003)	Singapore	Tropical	Adults	0.60	Estimated	1.2	Estimated	A/C	25.8
Wong and Khoo (2003)	Singapore	Tropical	13-18	0.45	Estimated	1.2	Estimated	NV	28.8
Ahmad and Ibrahim (2003)	Shah Alam, Malaysia	Tropical	Adults	0.60	Estimated	1.2	Estimated	NV & A/C	27.6 in NV 26.5 in A/C
Kwok and Chun (2003)	Tokyo, Japan	Sub-Tropical	13-15	0.37	Estimated	1.2	Estimated	NV & A/C	27.5 in NV 23.1 in A/C
Wang and Wang (2006)	Harbin, China	Tropical	Adults	0.57	Estimated	1.2	Estimated	NV	N/A
Hwang *et al.* (2006)	Center and South Taiwan	Sub-Tropical	Adults	0.60	Estimated	1.2	Estimated	NV&A/C	26.3
Corganti *et al.* (2007)	Turin, Italy	Mediterranean	15-17	N/A	N/A	1.2	Estimated	Hybrid	21.5
Hussein and Rahman (2009)	Malaysia	Tropical	6-17	0.50	Estimated	1.2	Estimated	NV	28.4
Ben Hussein *et al.* (2009)	Malaysia	Tropical	Adults	0.50	Estimated	1.2	Estimated	NV&A/C	23.1-25.6 in A/C 26-30.7 in NV
Al-Rashidi *et al.* (2009a)	Kuwait	Hot, dry	11-17	1.17 boys 0.95 girls	Measured[2]	1.2	Estmated	Hybrid	21.5
Al-Rashidi *et al.* (2009a)	Kuwait	Hot, dry	11-17	1.17 boys 0.95 girls	Measured[2]	1.2	Estimated	NV	21.6
Fong et al. (2010)	Hong Kong	Tropical	Adults	0.57	Estimates	1.0	Estimated	DM	27.0
Al-Rashidi *et al.* (2010)	Kuwait	Hot, dry	11-17	0.65 boys 0.73 girls	Measured[2]	1.2	Estimated	A/C	23.7

NV: Natural Ventilation; A/C: Air-Conditioning;; Hybrid: Air-Conditioning system is turned on and off during different parts of the day; DM: different ventilation modes; mixing; displacement and stratum; N/A: Not available; [1]with Havenith (2007) corrections, [2]Using thermal manikins with adult size clothing.

2.1.11 Effect of air movement on thermal comfort in hot climates

This section reviews the fundamentals of physiological cooling effect due to internal air movement on human comfort as well as the results of studies carried out previously with regard to velocities of air to lower high internal temperatures and also the upper acceptable velocity limits.

Among the six variables that influence thermal comfort, air speed is proposed as the most critical aspect especially in hot and humid regions since it greatly influences thermal comfort of humans in buildings.

Increasing indoor airspeed is suggested as a useful way to improve human thermal in buildings found in hot and humid climatic regions (BYRNE *et al.*, 1985; Hyde, 2000; PRIANTO *et al.*, 2000; Hirunlach, Wachirapuwadon, S., Prathinthong and Khedari, 2001; Toftum, 2004; Turner *et al.*, 2008; Chow *et al.*, 2010; Indraganti *et al.*, 2014; Toe, 2018). An increase in air floor in situations like this directly influences thermal comfort of humans (Givoni, 1998).

First an increase in the movement of air across the surface of the skin enhances heat transfer by convection which strongly improves thermal response (Fountain and A., 1993). Additionally, it enhances evaporation of sweat from the human skin therefore lowering discomfort caused by wet skin in conditions of high humidity (Givoni, 1994, 1998; Allard, 1998; Szokolay, 2004). These mechanisms together create a cooling effect as well as improve thermal comfort of humans. Thus, it is recommended to ensure appropriate high air velocities across the body of occupants in a room so as to achieve the needed evaporation (Givoni, 1998)g. When external temperature is lower that skin temperature (35°C), it is appropriate to raise the velocity of indoor air since cooling due to evaporative and convective effects can function in similar directions. It is worth noting that in hot and humid areas increasing air movement in a building might still be helpful and acceptable even if temperature of external air is higher compared to the temperature of indoor air (Givoni, 1994)since high air speed raises the upper level comfort temperature. The positive effect and preference of the velocity of indoor air on human thermal response was established in 1950s (Fountain and A., 1993); proposed that it is possible to raise thermal comfort temperatures by about 0.55K for each additional 0.15ms^{-1} elevation in in air flow over the skin surface of building occupants provided the temperature of indoor air does not go above 33°C.

(Givoni, 1969) carried out a physiological study and examined the impact of air velocities as high as 4 ms^{-1} on thermal comfort of humans; the regular pleasant sensation was observed. Occupants were found to be comfortable at 30°C indoor air temperature and air velocity of 2 ms^{-1} and did not notice the excess wind (Givoni, 1992). A different study by Givoni showed that an increase in the speed of air indoors reduced heat perception and enhanced human comfort since its increased heat loss through convection and lowered skin temperature. This was so particularly at indoor air temperatures lower than 33°C (Givoni, 1998).

Even when air temperatures exceeded 37°C, increasing indoor air velocity would still be appropriate as this would reduce wetness of the skin (Givoni, 1998). Givoni further proposed an internal air speed of $1.5\, ms^{-1}$ as suitable for enhancing comfort at 28°C maximum surrounding temperature while for a maximum temperature of 32°C an internal air speed of $2\, ms^{-1}$ was suitable provided that the range of diurnal temperature is below 10°C. This can be seen in Figure 2-5 (Givoni, 1991, 1992, 1998).

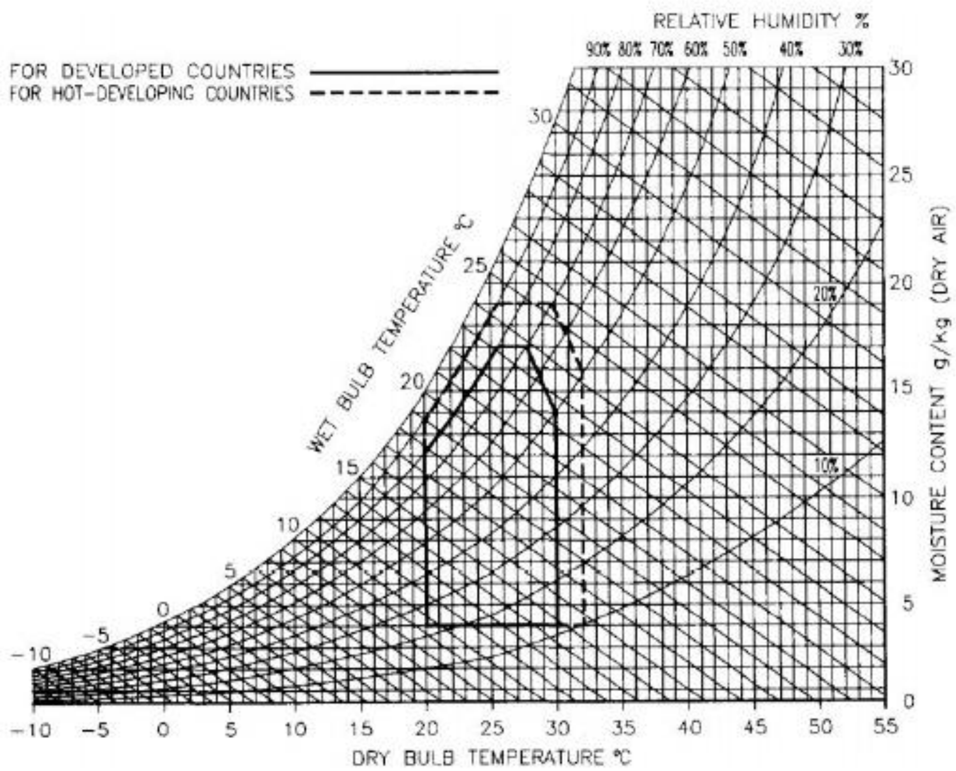


Figure 2-5 - Extended comfort boundaries (air speed of 2 m/s) (Givoni, 1992).

Several studies carried out in hot and humid climatic conditions also support the effect of elevating air flow to offset high indoor temperatures and bring about a cooling effect as well as increase the upper boundary temperature of comfort as listed in Table 2-5.

Table 2-5 - Elevated air movement (cooling effect) for high temperature (studies)

Year	Climate	Findings	References
2001	Tropics (Thailand)	The upper limit of comfort in Thailand extended to 29.1°C, 29.9°C and 31.3°C with air speed of 0.2ms-1, 0.4ms-1 and 1.0ms-1, respectively.	(Tantasavasdi *et al.*, 2007)
2003	Tropics (France)	Air speeds of 0.1ms-1 to 2.0ms-1 provided occupants' thermal comfort in a house under room temperature of 28°C with 70% RH.	(Prianto and Depecker, 2002)
2006	Tropics (Singapore)	People in the Tropics preferred elevated local air velocity to offset high room temperature. The air velocities from 0.3ms-1 to 0.45ms-1 were required for air temperature of 23°C, while higher velocities from 0.3ms-1 to 0.9ms-1 were required at ambient temperature of 26°C.	(Gong *et al.*, 2011)
2009	Tropics (South China)	The upper limit of comfort extended from 26°C to 29°C when air velocity was increased from 0.25ms-1 to 1.5ms-1. This limit could further extend to 29.5°C when the Predicted Percentage of Dissatisfied (PPD) increased from 10% to 20%.	(Lei, 2009)
2011	Tropics (North-east Brazil)	Minimum air velocity to achieve 90% of thermal comfort when air temperatures were between 24°C and 27°C, 27°C and 29°C, and 29°C and 31°C were found as 0.4ms-1, 0.41- 0.8 ms-1, and more than 0.81 ms-1, respectively.	(Candido, Dear and Lamberts, 2008)
2014	Tropics (South India)	The upper limit of comfort temperatures of the occupants in office buildings in India was increased by 2.7K to up to 30.1°C in natural ventilation and 28.6°C in a/c modes, when the air speed was increased for 1ms-1 due to the ceiling fans.	(Indraganti *et al.*, 2014)

In hot and humid climatic conditions, it has been established that the sensation of thermal comfort increases as air velocity is increased using electric fans. According to (Givoni, 1998), the comfort of occupants was examined in an indoor space with controllable ceiling fans; it was established that comfort levels increased when air temperature inside the indoor space was at 30°C with air speed of $2ms^{-1}$. Additionally (Spain, 1987) established that air flow with air speeds below 0.25 ms^{-1} or still air, air speeds ranging between 0.25 ms^{-1} and 1.5 ms^{-1} or moderate air and air speeds above 1.5 ms^{-1} or high air provided by ceiling mounted fans were capable of providing human comfort for indoor air temperatures of 27.8°C, 29.4°C and 29.4°C and above respectively (Spain, 1987).

Similarly, (Fountain and Arens, 1994) carried experiment based research to investigate the impact of air flow that can be controlled from nearby of speeds ranging from 0 ms^{-1} and 1 ms^{-1} and room air temperatures between 25.5°C to 28.5°C. The study was carried out in an office with large open space; the occupants were allowed to control internal air speed using a table fan. It was established that more occupants were pleased as air velocity increased (Fountain and Arens, 1994). The study provided a chart Figure 2-6 to predict the percentage of people satisfied (PS) with respect to air velocity and air temperature.

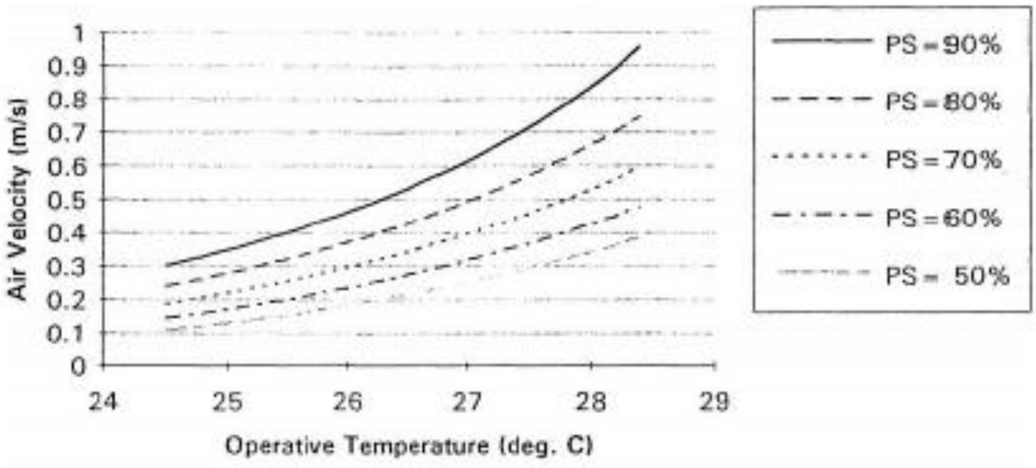


Figure 2-6 - (PS) of different air velocities (function of operative temperature) (Fountain and Arens, 1994).

Mallick (1996) also examined the impact of elevating air velocities from using ceiling fans 0.15 ms^{-1} to 0.45 ms^{-1}on the comfort of occupants for various air temperatures ranging from 24°C to 32°C and relative humidity from 50% and 90% in Bangladesh which experiences hot and humid conditions; the study established that comfort temperature ranges increased with an increase in air velocity. Nonetheless this was found to be effective for particular values as shown in Table 2-6 ; for speeds less than 0.3ms^{-1} no substantive increase in comfort was observed. Hence the study concluded that air speeds lower than 0.3ms^{-1}could only enhance air quality indoors but not offer thermal comfort or cooling effect (Mallick, 1996).

Table 2-6 - Comfort temperatures for different air speeds due to ceiling fans under hot-humid climate of Bangladesh (Mallick, 1996).

Fan speed setting	**Air speed (ms^{-1})**	**Comfort Temperature Range (ºC)**	**Mean Comfort Temperature (ºC)**
None	0	24-33	28.9
Low	0.15	24-33	29.5
Medium	0.3	26.4-35.2	30.9
Fast	0.45	27-35.8	31.6

Khedari et. al., (2001) further back the effectiveness of ceiling mounted fans in widening comfort zones particularly in hot and humid climatic areas. From results obtained through questionnaires, the researchers came up with a chart in Figure 2-7 to identify the needed air velocity to offset high indoor temperatures for relative humidity ranging from 50% to 80%. It was found that an electric fan generating air velocity of 0.2 ms^{-1} provided thermal comfort for an indoor air temperature of 26°C and one generating air speed of 3.0 ms^{-1} provided comfort for an indoor air temperature of 36°C. Increasing air speed by 1.0 ms^{-1} effectively reduces the temperature sensed in comfort terms by 2K to 6K depending on percentage relative humidity. Relative humidity is also very important; the effectiveness of elevating air flow to enhance comfort reduces with increased relative humidity. The study further proposed that low air speeds such as 0.2 ms^{-1} was enough to provide comfort at 28°C indoor air temperature while temperatures higher than 34°C required higher velocities such as 3.0ms-1 (Hirunlach, Wachirapuwadon, S., Prathinthong and Khedari, 2001).

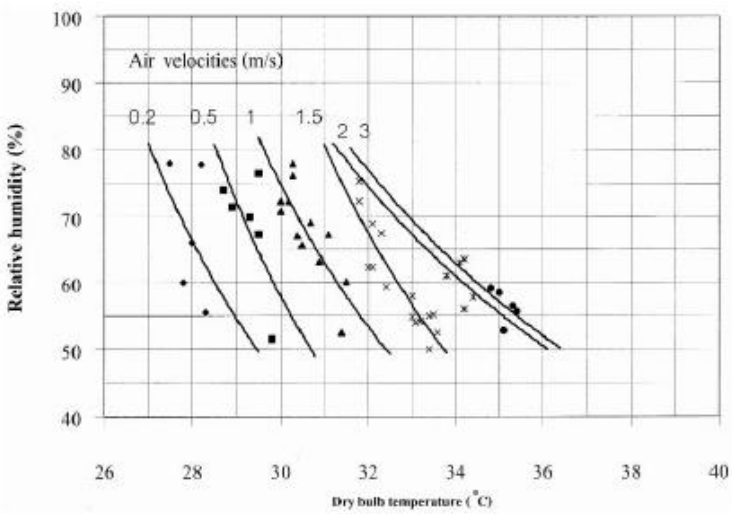


Figure 2-7 - Ventilation comfort chart for (offices, classrooms) in Thailand (Hirunlach, Wachirapuwadon, S., Prathinthong and Khedari, 2001).

Indraganti et. al., (2014) carried out an extensive survey study that backed the effectiveness of ceiling mounted fans in enhancing thermal comfort. The study was conducted in Indian cities which experience hot and humid climatic conditions; it was established that for naturally ventilated buildings an increase of approximately 1 ms^{-1} in indoor air speed increased the average comfort temperature by about 2.7°C to 30.1°C and 28.6°C for air conditioned buildings (Indraganti *et al.*, 2014).

Additionally, elevating air flow is also suitable for air-conditioned indoor spaces. Chow et al., (2010) conducted an experiment based study examining occupants' thermal perception in an air conditioned office space in Hong Kong; a hot and humid country, for temperatures between 25°C and 30°C and relative humidity between 50% to 85%. Table 2-7 shows the effect of elevating air velocity on thermal comfort boundaries. Increasing air velocity from values below 0.2 ms^{-1} resulted in the extension of the upper limit comfort temperature from 24.9°C to 26.4°C and increasing air speed to 1.0 ms^{-1} increased the upper limit comfort temperature from 26.8°C to 28.3°C which is an increase of about 1.5°C.

Table 2-7 - Different room temperatures (Comfort air speeds) at working environment with a/c systems under the climates of Hong Kong (Chow *et al.*, 2010).

Air Temperature (°C)	**Comfort air speed (ms^{-1})**	**Range of air speed for 90% comfort (ms^{-1})**	
		Lower bound	**Upper bound**
25	<0.2	0	0.99
26	0.59	0	1.63
27	1.22	0.18	2.26
28	1.85	0.81	2.9
29	2.49	1.45	3.53
30	3.12	2.08	4.17

It was established that air speeds of about 0.2 ms^{-1} were suitable for internal air temperature of 25°C and higher velocities ranging from 1.2 ms^{-1} to 3.1 ms^{-1} were needed for higher temperatures ranging from 27°C to 30°C. The study also found that increasing air speed by up to 1 ms^{-1} resulted in an off set of high indoor air temperatures by about 2°C. It was also established that for air-conditioned buildings in tropical regions the maximum thermal comfort temperature was higher than what was proposed by ASHRAE. It was therefore concluded that elevated air flow strategy is both cheap and effective in enhancing indoor thermal comfort in hot and humid area compared to reducing air humidity or temperature.

The proposed air velocities for various temperatures of air from the literatures reviewed; it shows the suitable air velocities between 0.1 ms^{-1} and 3.1 ms^{-1} recommended to enhance thermal comfort for air temperatures between 25°C and 35°C. According to the chart, higher air speeds are needed to provide human comfort for higher indoor temperatures.

Table 2-8 - Preferred air speeds equations compensating high air temperatures from past literatures (Chow *et al.*, 2010).

References	Findings
Drysdale (1952) (Szokolay, 2000)	Suggested air speed of 0.15ms^{-1} to compensate for 1K, for air speed up to 1ms^{-1} and air temperature up to 37°C and proposed a function as: $$dT = 6.7v$$ Where dT is the cooling effect compensated by elevated air velocity (K), v is air velocity (ms^{-1}) at the body surface.
Rohles et al (1974) (Szokolay, 2000)	Suggested air speed of 0.48 ms^{-1} to compensate for every 1K, and proposed a function form as: $$dT = 2.08v$$
Aren & Watanabe (1986) (Szokolay, 2000)	Suggested the extensions to the comfort zone of Psychrometric chart using air velocity of 0.5 ms^{-1} for 3.1K. This gives a function as: $$dT = 8.26(v - 0.25)$$
Olgyay (1953)	Proposed Psychrometric chart and indicated the required air velocity of 0.5ms^{-1}, 1.0ms^{-1} and 1.5ms^{-1} to compensate for high air temperature of 2.5K, 5K and 7.5K, respectively.
Humphrey & Nicol (1995) (Szokolay, 2000);	Proposed the cooling effect (K) as a function of an elevated air velocity (ms^{-1}) as: $$dT = 7 - \left[\frac{50}{4+10\sqrt{v}}\right]$$
Szokolay (2000, 2014)	Proposed the preferred air velocity (ms^{-1}) to offset for high air temperature (K) as a function below: $$dT = 6Ve - (1.6Ve)$$ Where Ve is an effective velocity, which is equal to $v - 0.2$ ms^{-1} and it should be noted that this expression is valid up to 2ms^{-1}.

From the literatures reviewed there is a broad range of air velocities proposed to offset high indoor air temperatures, but the literatures do not provide specific air velocities for exact air temperatures. This can be attributed to the fact that thermal and comfort perceptions vary based on several variables and can also vary from one individual to another. The results of the studies however support the fact that physiological cooling caused by elevated air flow is effective in lowering indoor air temperatures and hence improving thermal comfort in buildings especially in hot and humid regions.

The Szokolay model (Szokolay, 2004; Auliciems and Szokoloay, 2007), provides the mean of the results obtained through comprehensive research on the cooling effect due to elevated air movement; this is shown in Table 2-8 and can be employed in approximating the needed air speeds for specific indoor air temperatures. It is evident that elevated air speeds lead to improve thermal comfort conditions in hot and dry climates. As ventilation mechanisms have the added advantage of energy efficiency and improved indoor air quality, these systems are described in detail in the following sections.

2.2 Limits of acceptable air velocity for hot climates

Even though elevated air flow is desirable and at times needed to create a cooling effect and enhance thermal comfort, in some cases high indoor air speed may be uncomfortable and a nuisance. International guidelines and standards have been developed to address this issue; ASHRAE Fundamentals (2013) for instance sets the maximum acceptable indoor air velocity to $0.8ms^{-1}$. Air flow rate above this stipulated velocity may cause disturbance for example flying papers in an office setting surrounding air flow (Givoni, 1994). On the other hand (Hyde, 2000; Olgyay, 2015) proposed a maximum speed of 1 ms^{-1} to avoid discomfort. Additionally, Olgyay (2015) described pleasant air movement as air flow when indoor air temperatures fall above 23.9°C and unpleasant air movement as air flow when indoor air temperatures fall below 23.9°C. He further illustrated the possible effect of various air velocities on a human being as shown in Table 2-9.

Table 2-9 - human perception and effect of air speed (Olgyay, 2015).

Air speeds (ms^{-1})	**Probable effect on human**
Up to $0.25ms^{-1}$	Unnoticed
$0.25\text{-}0.51ms^{-1}$	Pleasant
$0.51\text{-}1.02ms^{-1}$	Generally pleasant with a constant awareness of air movement
$1.02\text{-}1.52ms^{-1}$	Slight draught to annoying draught
Above $1.52ms^{-1}$	Requires corrective measures if work and health are to be kept in high efficiency

A similar conclusion was reached at by Szokolay (2007) with respect to individual responses to various air velocities; illustrated in Table 2-10. From the study air flow speeds lower than 0.25 ms^{-1} appeared not to have any effect on human occupants; those between 0.5 ms^{-1} and 1 ms^{-1} were created a pleasant feeling while speeds above 1 ms^{-1} created discomfort. It is thus recommended that occupants be given total control over surrounding air movement in environments with very high air velocities.

Table 2-10 - Different air speed and subjective reactions (Auliciems and Szokoloay, 2007).

Air speeds (ms^{-1})	Subjective reactions
Up to 0.1ms^{-1}	Stuffy
Up to 0.2ms^{-1}	Unnoticed
Up to 0.5ms^{-1}	Pleasant
Up to 1.0ms^{-1}	Awareness
Up to 1.5ms^{-1}	Draughty
Above 1.5ms^{-1}	Annoying

Nevertheless these proposed maximum air speed limits very restrictive particularly for people in hot areas since those living in buildings that are naturally ventilated are typically used to and prefer a broader temperature range and consequently higher speeds (Givoni, 1994). It is so because there is a close relationship between the desirable air flow rate and climatic conditions one is used to; there was a higher possibility of occupants perceiving air movement as unacceptable in environments with cool and moderate temperatures ranging from 22°C and 23°C. For indoor air velocities of 0.4 ms^{-1} and below and temperatures above 23°C draught typically did not occur (Toftum, 2004).

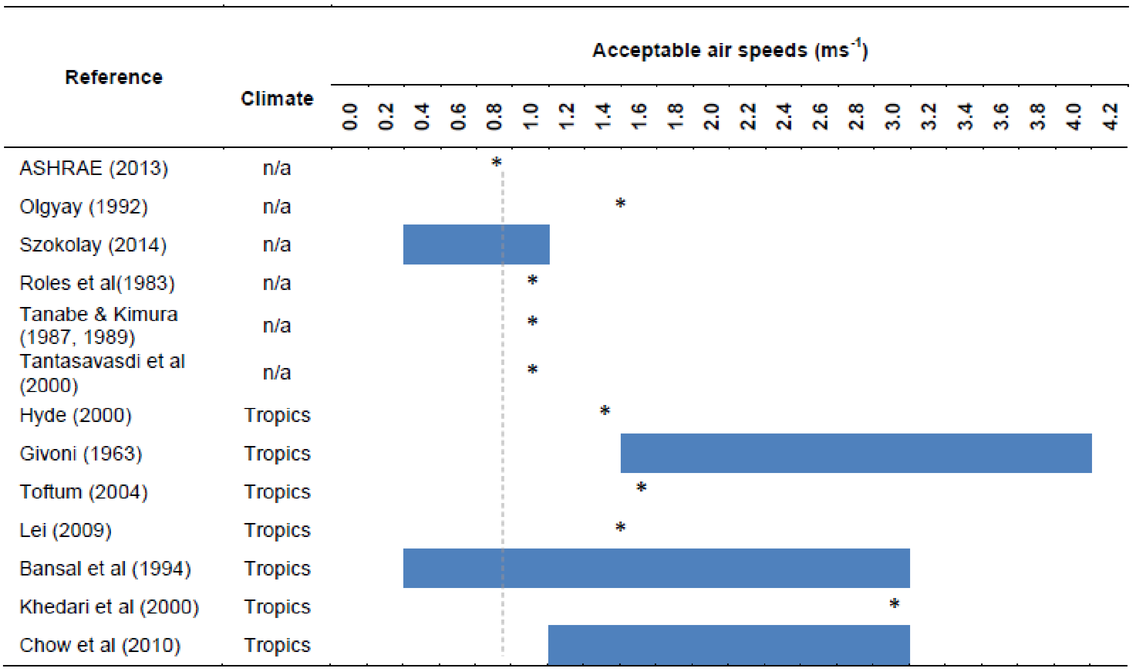
Givoni (1969) carried out a research to determine the physiological effect of air velocities on thermal indoor comfort. The results of Givoni's study showed that occupants were comfortable and remained undisturbed at air velocity as high as 2 ms^{-1}; this feeling of comfort was observed even when air velocity was increased to as high as 4 ms^{-1} (Givoni, 1969). Additionally Givoni (1991) described indoor air velocities ranging between 1.5 ms^{-1} and 2.0 ms^{-1} extremely light air movement that facilitates human comfort particularly in hot and humid areas. These desirable air velocities termed as disturbing by some studies (Auliciems and Szokoloay, 2007; Olgyay, 2015) are definitely extremely higher than the maximum limit proposed by ASHRAE. Additionally, many studies recommend higher air speeds than the one recommended by ASHRAE to enhance thermal comfort in hot and humid areas; shown in Table 2-11.

Table 2-11 - Hot climates acceptable air speeds (Auliciems and Szokoloay, 2007).

References	Findings
Roles et al (1983), Tanabe & Kimura (1987,1989) in (Fountain and Arens, 1993) and Tantasavasdi et al in (Tantasavasdi et al., 2001)	Suggested air speeds as high as $1ms^{-1}$ for restoring comfort in hot climates.
Lei in (Lei, 2009)	Suggested air speed as high as $1.5ms^{-1}$ for offsetting high temperature in the warm-humid climate of Southern China.
Bansal et al in (Bansal et al., 1994a)	Suggested the range of wind speed between $0.53ms^{-1}$ and $3.04ms^{-1}$ with the minimum of $0.29ms^{-1}$ for warm and humid climates.
Khedari et al in (Khedari et al., 2000c)	Suggested air speed of up to $3ms^{-1}$ offset for high room temperature (above 34°C) during summer of Thailand.
Candido et al in (Cândido et al., 2010)	Concluded that the people in the tropics prefer higher local air speed range than the maximum velocity permissible by ASHRAE Standard even in the situations where the subjects have no control over local air movement.
Chow in (Chow et al., 2010)	Found that occupants in a/c environments preferred air speeds above $0.2ms^{-1}$ under indoor air temperature at 25°C and that of $1.2ms^{-1}$ to $3.1ms^{-1}$ at 27°C and 30°C.

Table 2-12 According to Givoni (1969), the velocity of air in a room with single-sided ventilation ranges between 10% and 20% of the prevailing speed of wind whereas in a room with cross ventilation the speed of air inside a room could be between 30% and 50% .The speed of air floor in a room is determined by the position and size of openings with respect to the direction and speed of external wind and the vertical distance between the outlet and inlet openings. compares air velocity ranges established as suitable in hot and humid regions with the maximum acceptable air speed proposed by ASHRAE. From Table 2-12 a broad range of the air velocities proposed lie between 0.2 ms^{-1} and 4 ms^{-1}; in this table the asterisk symbol **(*)** indicates the maximum air speeds proposed in a specific study while the suitable air speed ranges are indicated by dark blue lines. It is clear that maximum acceptable levels proposed are way above the acceptable air velocity proposed by ASHRAE; this is especially true for all studies conducted in tropical areas. This can be attributed to the fact that the maximum acceptable air speed proposed by ASHRAE was based on an office set up in a cold climatic region.

Table 2-12 - literatures review acceptable air velocity.



Hence ASHRAE's limit is much lower than what would be suitable or acceptable by occupants in buildings naturally ventilated in tropical areas and specifically classroom buildings in Kuwait. For such a case the maximum acceptable air speed relies on the comfort produced and is dependent on relative humidity and temperature. For people living in hot countries have typically become used to high temperatures and consequently would still be comfortable with air speeds higher than the one recommended by ASHRAE.

2.3 Mechanisms of natural ventilation

When a difference in pressure (*$\Delta\rho$)* between the environment inside and outside a building results in wind or stack forces, it facilitates natural ventilation (Clements *et al.*, 2008). The basic mechanisms of natural ventilation are now briefly described.

2.3.1 Wind force:

The distribution of wind pressure around a building is determined by the building's geometry and its orientation with respect to the direction of the wind. Natural ventilation can develop within different sides of the building experiences difference in wind pressures (Clements *et al.*, 2008). A building's windward side also known as pressure zone experiences positive wind coefficients and the buildings leeward side also known as suction zone experiences negative wind pressure coefficients. The side facades of the building can experience negative or positive wind pressure coefficients depending on their orientation relative to the direction of the wind; this is shown in Figure 2-8

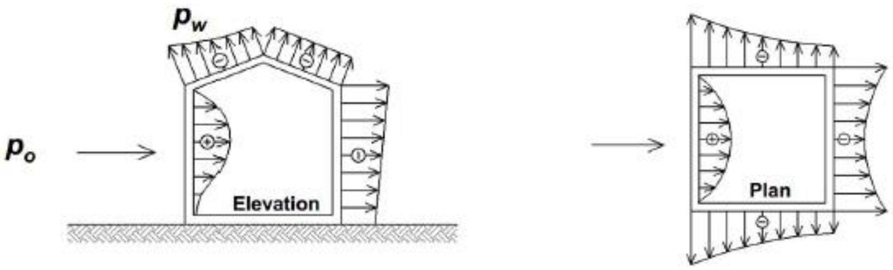


Figure 2-8: Pitched Roof Building and Wind Pressure Distribution (Clements *et al.*, 2008).

Hence the major factor that determines the wind-driven rate of air flow in the building is the difference in pressure between the openings found on the building and the size of openings. To analyse the rate of airflow inside a building as a result of wind force, it is required to determine the distribution of wind pressure in every opening in the building. Usually wind pressure on a building's surface is not evenly distributed; as wind pressure distribution decreases from the centre of the building's pressure zone, outwards as described by Equation 3.1 which can be used to estimate pressure distributions at various points of a building *(Clements* et al.*, 2008)*.

$$p_w = 0.5\ C_p \rho_o \bar{V}^2 \quad \ldots\ldots\ldots\ldots\ldots \qquad \textbf{Eq 2.1}$$

In Equation 2.1, wind pressure is denoted by p_w, air density denoted by ρ_o, V denotes the speed of wind at datum level; this speed is usually with respect to the opening height or measured from a specific reference point for example the roof (ms^{-1}) while **C_p is the pressure coefficient** which is dimensionless.

The pressure coefficient C_p varies depending on the configuration of the building in terms of the direction and velocity of wind as well as the building' s geographical location and the vegetation in its surrounding (Klevien, 2003). Since C_p is dependent on a number of factors, various points on the surface of a building tend to have different values of pressure coefficient. It is for this reason that it is difficult to exactly determine the value of C_p at a given point on the surface of the building. Previously prediction of C_p values was made inside a wind tunnel through pressure measurement, resulting in Eq.2.2 which could also be used to estimate the value of wind pressure coefficient.

$$C_p = (p - p_o)/0.5\, \rho_o \bar{V}^2 \qquad \ldots\ldots\ldots.. \qquad \textbf{Eq 2.2}$$

In Eq. 2.2, p represents static pressure at a particular point on the surface of a building (Pa), p_o represents static pressure of free wind stream that corresponds to V_r (Pa), V represents the velocity of free wind stream which is calculated with respect to the height of a particular opening or from a particular reference height (ms^{-1}) while ρ_o is the density of the free stream in (kgm^{-3}). It is possible to determine the speed of wind at a particular height as a function of wind speed measure at a height 10m above ground surface; the Meteorological Office normally measures and records this using the ‘Power law’ wind profile denoted as Eq.2.3.

$$\frac{V_1}{V_{10}} = K\, {z_1}^a \qquad \ldots\ldots\ldots \qquad \textbf{Eq 2.3}$$

V_1 is the speed of wind in ms-1 at a height z1meters while V_{10} is the speed of wind at a height 10 meters from the ground. *K* denotes the pressure coefficient while *a* is an exponent dependent on the nature of the terrain (Santamouris, 2005).

Computational Fluid Dynamics simulation (CFD) can also be used to estimate the wind pressure coefficient. CFD has been in used from the 1970s and there are also other recently developed packages available for the purpose. Some simulation software packages are only capable of estimating average C_p values for different facades on a building while others are capable of predicting the value of C_p at specific points in a certain facade under certain conditions. *CPBANK* for example was created from the outcomes obtained through extensive tests carried out in a wind tunnel laboratory; and it is capable of estimating average value of C_p on a building facade with particular shapes, arrangements and orientation (Ghiaus and Allard, 2012). On the other hand, *CpCalc+*, proposed by the *PASCOOL* project (Allard, 1998), and *CpGenerator*, developed by TNO Building Research, can predict the value of C_p at specific points in a certain facade under certain different building conditions; shape, surroundings and orientation. *CpCalc+* and *CpGenerator* both were developed using data obtained through experimental studies or literature review and both have the same capabilities and approaches.

2.3.2 Stack or buoyancy force:

In a building, stack force is created at an opening through changes in air density resulting in differences in temperature between the inside and the outside of the building as well as over the openings found on the building envelope (Auliciems and Szokoloay, 2007). Stack pressure is created in a significantly tall building that has one big opening or at least two openings at different heights; this is shown in Figure 2-9(a) and Figure 2-9(b). Additionally, stack pressure occurs in a building with vertical stack as shown in Figure 2-9(c).

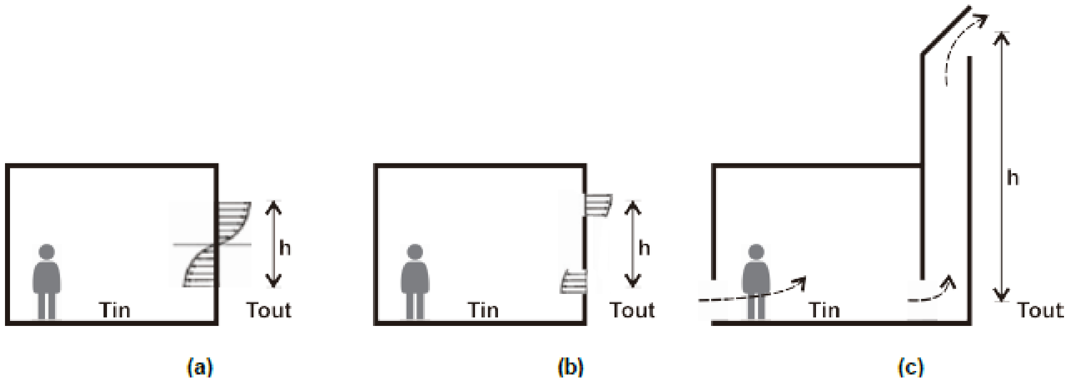


Figure 2-9: Stack natural ventilation: (a) one large opening room; (b) two different height openings room; (c) vertical stack room; (Auliciems and Szokoloay, 2007).

If the temperature of air indoors is higher than outside the building, the indoor air pressure at higher levels in the building will be higher than that of the outside, while a low pressure will exist at lower heights in the building. As warm air is lighter than cold air, it moves up to the building's upper section and is expelled through the higher level opening while colder air gets in through the lower opening and replaces the warn air in the building that has been expelled out. The following Eq.2.4 can be used to calculate stack pressure (Clements et al., 2008).

$$p_s = -\rho_o g h (1 - \frac{T_o}{T_i}) \quad \text{.........} \qquad \textbf{Eq 2.4}$$

In this equation T_o is the reference temperature or temperature outdoors (K), T_i is the temperature of air indoor (K), ρ_o represents the density at T_o or reference temperature (kgm^{-3}), g represents gravitational acceleration which is equal to 9.81 ms^{-2} while h height difference between the openings (m).

Stack force can also be created by the distance up to the Neutral Plane Level (NPL) (Ghiaus and Allard, 2012). Neutral Pressure Level occurs at a height where inside and outside pressures are equal. At this level there is balanced airflow, which means air entering the building is equal to air leaving the room. Air above the NPL will be expelled through the outlets in the building while air below will be forced in through the inlets. The position of the NPL in a building is dependent on the position and size of the building openings temperature difference between indoor and outdoor air and state of wind outside the building. The NPL normally occurs near the biggest openings and its position can be estimated using Eq.2.5 (Klevien, 2003).

$$h_o = \frac{{A_1}^2 h_1 + {A_2}^2 h_2}{{A_1}^2 + {A_2}^2} \qquad \ldots\ldots\ldots\ldots \qquad \textbf{Eq 2.5}$$

In this equation h_o represents the NPL from the ground level (m), A_1 is the lower opening area (m^2), A_2 is the upper opening area (m^2), h_1 is the vertical distance from the floor to the lower opening (m) and h_2 is the vertical distance from the floor to the upper opening (m).

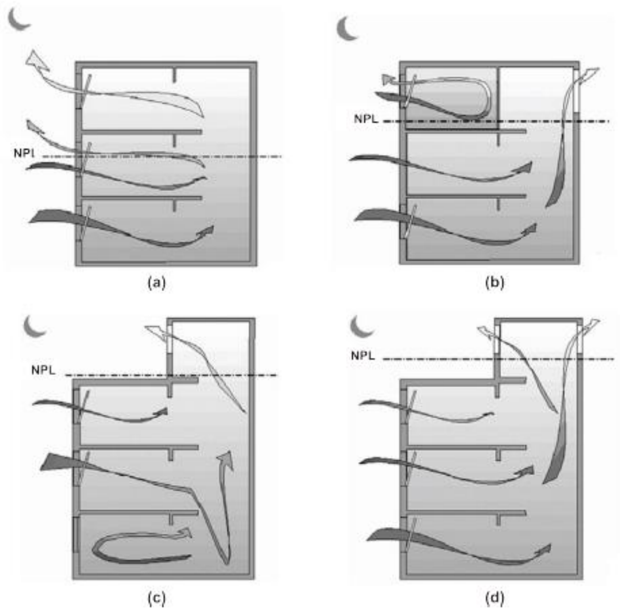


Figure 2-10: Different opening designs room with different NBL Locations (Ghiaus and Allard, 2012)

It is evident from Eq.2.4 and Eq.2.5 that stack force is highly dependent on temperature difference as well the height difference between the inlet and outlet in the building. Stack pressure increases with increase in temperature and distance between the outlet and inlet and as stack pressure increase so does the rate of air flow inside the building.

Generally, the rate of indoor airflow as a result of stack force is lower than airflow rate resulting from wind force. Since airflow rate due to stack force is dependent on height difference and temperature between the inlet and outlet openings in a building, the effect of stack force is comparably lower in structures that are a few storeys tall (e.g. 1 or 2) especially in warm areas where indoor and outdoor temperature difference is also small.

2.3.3 Combined wind and stack forces:

Airflow inside a building is usually due to the effect of both the wind and stack forces, as they typical act together (Awbi, 2013). The two forces may act in the same direction and reinforce each other or act in different directions and cancel out each other. This is depicted in Figure 2-11 (a) and (b).

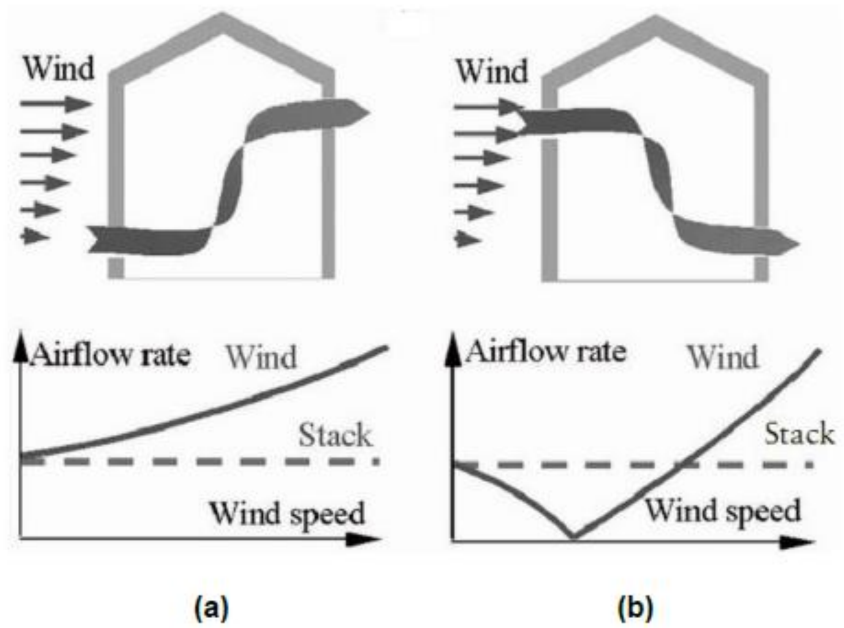


Figure 2-11 - Wind and Stack forces combined effect: (a) combined wind and stack forces effect; (b) Wind and Stack forces obstructed effect (Ghiaus and Allard, 2012) .

2.3.4 Principal designs for of natural ventilation in buildings:

The design principles that allow increased natural ventilation can be categorized into three: single-sided ventilation, cross ventilation and stack ventilation, as shown in Figure 2-12.

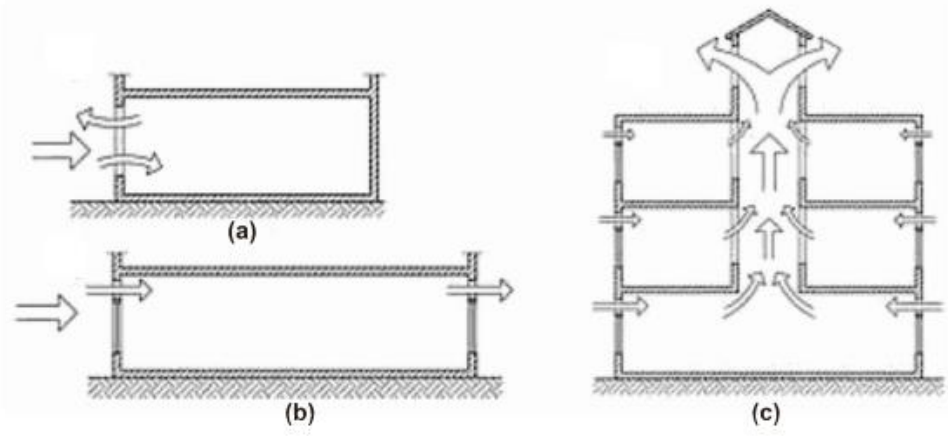


Figure 2-12 : Principle designs for natural ventilation: (a) single-sided; (b) cross ventilation; (c) stack (Awbi, 2013).

2.3.4.1 Single-sided ventilation:

This type of ventilation is characterized by air naturally entering and leaving a building from a single opening or through different openings that are situated on a single side of the building as shown in Figure 2-12(a). Air movement in a building with single sided ventilation generally is due to a combination of stack force and wind force which are dependent on external wind velocity and temperature difference inside and outside the building (Larsen and Heiselberg, 2007). With this design, the vertical location of the room is an important issue. A study carried out by Allocca et. al., (2003) in which the room under study was located midway in a three floor building, there was reverse air flow when external air velocity increased from between $3ms^{-1}$ and $8ms^{-1}$. Airflow dominated by wind force is normal during summer in countries with hot and humid climatic conditions, as during this period the speed of wind is quite high and the temperature difference between the inside and the outside buildings is substantially low. The study further suggested to enhance the performance in single-sided ventilation by including at least two opening in the design of the building, and to have the openings at unequal height levels to add stack effect (Allocca, Chen and Glicksman, 2003). Although this design is widely used in practice due to ease of implementation, it has a number of disadvantages. These include difficult to control air flow, low air speeds and is only effective in spaces near the opening. A number of studies carried out including studies by CIBSE and UK's Building Research Establishment (BRE) , proposed that for healthy indoor ventilation to be achieved in a single-sided ventilation, the depth of a room should be 2 to 2.5 times the height from building floor to the ceiling or a lower than six meters (Klevien, 2003; Clements *et al.*, 2008; Ghiaus and Allard, 2012; Awbi, 2013). Nevertheless, airflow rate would be low, hence single-sided ventilation is suitable for offering healthy indoor ventilation but is unable to offer comfort inside buildings or produce that cooling effect in hot and humid areas.

2.3.4.2 Cross ventilation

This is a ventilation principle where air gets into an indoor space through an opening on located on one of the sides of a building, this air moves through space inside the building and then leaves the building through an different opening on a different side of the building, the opening can be on an adjacent or opposite wall as shown in Figure 2-12(b) *(Awbi, 2013)*. Cross ventilation is also known as two-sided ventilation. Air from outside the building is forced into the building through openings located on the windward side of the building and forced out through the openings on the leeward side of the building by wind force. Stack force acts when the vertical distance between building openings is significant. Carrilho da Graça et. al., (2016) suggests that cross ventilation mechanism is efficient even for rooms with maximum depth of 12 meters, or a depth of about 2.5 to 5 times of roof or ceiling the height (Klevien, 2003). Additionally cross ventilation poses as a straightforward natural ventilation mechanism that is effective for rooms in hot and humid climatic regions; it gets rid of heat inside a building and enhances human comfort through enhancing physiological cooling effect (Ghiaus and Allard, 2012).

According to Givoni (1969), the velocity of air in a room with single-sided ventilation ranges between 10% and 20% of the prevailing speed of wind whereas in a room with cross ventilation the speed of air inside a room could be between 30% and 50% .The speed of air floor in a room is determined by the position and size of openings with respect to the direction and speed of external wind and the vertical distance between the outlet and inlet openings Table 2-13.

Roy et. al., (1982) suggested a method to estimate the average velocity of air inside a room that is cross ventilated and does not have internal partition with the room subjected to different directions of wind and the size of the openings varied, shown in Table 2-14. The results of the study showed that the average velocity of indoor air increased with increase in the width of the openings; the average air velocity was highest with maximum width of outlet and inlet that is when the width of the openings was made equal to the width of the walls in the room. In addition, the study showed that a building or room-oriented oblique to the direction of external wind had a comparably higher average air speed than a room perpendicular to the direction of the wind at different sizes of openings.

The results above confirm the suggestion made by Givoni (1994) that a building should be oriented oblique to the direction of wind. Givoni (1994) further suggested that openings should be positioned on adjacent walls and not opposite walls since with openings positioned on walls opposite to each other air from outside would be forced from inlet opening directly out through the outlet. This way, only a small part of the room would be ventilated as shown in Figure 2-13(a). If the openings are on adjacent walls, then external air would circulate through a broader area of the room and the average air velocity would be higher as the air changes direction in the room as shown in Figure 2-13(b).

Table 2-13 - Average indoor air velocity in ventilated (Single/Cross) rooms (as a percentage of external wind speed) (Givoni, 1994).

Natural ventilation principle	Location of openings	Wind direction (Incident to opening(s))	Total width of openings/ Indoor air velocity as percentage to external wind speed (%)			
			2/3 of the wall		3/3 of the wall	
			Average	Maximum	Average	Maximum
Single-sided ventilation	Single opening in pressure zone	Perpendicular	13	18	16	20
		Oblique	15	33	23	36
	Single opening in suction zone	Oblique	17	44	17	39
	Two opening in suction zone	Oblique	22	56	23	50
Cross ventilation	One opening in pressure zone and another in adjacent wall	Perpendicular	45	68	51	103
		Oblique	37	118	40	110
	One opening in pressure zone and another in suction zone	Perpendicular	35	65	37	102
		Oblique	42	83	42	94

Table 2-14 - Average indoor air velocity in ventilated room (cross) with different opening sizes under two wind directions (Allard, 1998).

Wind direction	Opening sizes according to the wall's width		Average indoor air velocity as percentage to external wind speed (%)
	Inlet width	Outlet width	
Perpendicular	1/3	1/3	35
	1/3	2/3	39
	1/3	1	44
	2/3	1/3	34
	2/3	2/3	37
	2/3	1	35
	1	1/3	32
	1	2/3	36
	1	1	47
Oblique (45°)	1/3	1/3	42
	1/3	2/3	40
	1/3	1	44
	2/3	1/3	43
	2/3	2/3	51
	2/3	1	59
	1	1/3	41
	1	2/3	62
	1	1	65

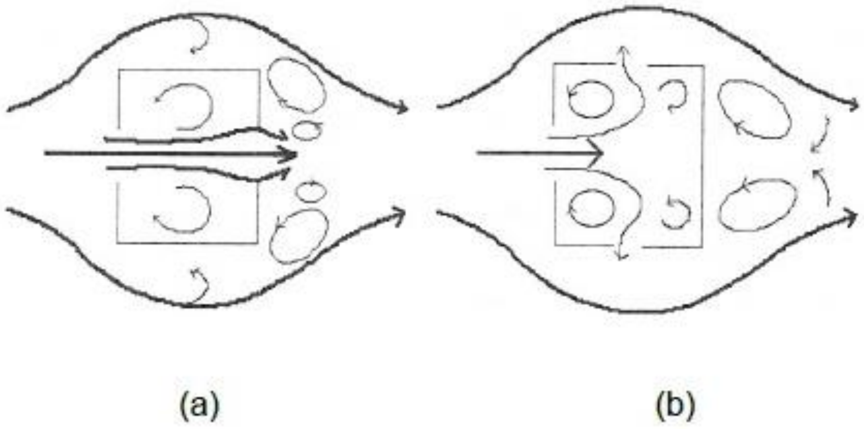


Figure 2-13 - Pattern of Airflow in and around a building (a) opposite walls two openings; (b) adjacent walls two openings (Pavlou, Vasilakopoulos and Santamouris, 2009).

Tantasavasdi et. al., (2007) used CFD code (*PHOENICS*) to investigate the velocity of air inside a room in a 2-floor building using different ventilation principles; cross ventilation with two openings located on walls opposite to each other, two sided ventilation with two openings located on walls adjacent to each other and single sided ventilation. Their study showed that cross ventilation and two-sided ventilation had much higher air velocities compared to single-sided ventilation. Cross ventilation principle produced higher average air velocities and uniform distribution compared to two-sided ventilation principle even with openings of similar areas. This does not correspond to what Givoni (1969) suggested. The differences in the results by (Givoni, 1969; Tantasavasdi *et al.*, 2007) are attributed to the fact different tools were used for the two studies; Givoni measured velocities in few locations due experimental limitation while velocities across the room was determined using CFD.

The study carried out by Tantasavasdi et. al., (2007) with openings on walls opposite to each other resulted in uniform distribution of air in the room and higher average air velocities over the room. In addition their study showed that with cross ventilation when the area of the opening increased 20% above the area of the floor, the average air velocities across the room decreased; this is due to short circuiting when air from outside moved directly from inlet opening to outlet opening Tantasavasdi et. al., (2007).

From the analysed literature, cross ventilation and in particular a room or indoor space with openings positioned on opposite walls, one located on the building’s windward side while the other on the leeward side of the building is the most suitable to produce uniformly distribution of airflow and high average air velocity which is enough to enhance the comfort of the building in a hot and humid environment.

2.3.4.3 Stack ventilation

When the needed air movement inside a building or a room cannot be realized by the effect of wind force alone then stack ventilation can be implemented to enhance the air movement. The effect of stack force is relatively small and to achieve much better results, it may be necessary to make use of big openings or at least two openings located at different distances from the ground. Therefore, stack ventilation mechanism is better suited for tall buildings with more height space for example those with stacks or atria. Implementing a vertical shaft or stack with openings extending beyond the building can be useful in high rise buildings that have deep-plan arrangement. There is a high difference in pressure between the building window that serves as the inlet and the exhaust at the top of the stack that serves as the outlet; this pressure difference is increased due to the negative pressure induced at the opening of the stack. Consequently, air inside the building is forced up because of the high difference in pressure between the outlet and inlet. The orientation of the building with respect to the direction of wind has no effect on the stack ventilation; the performance of stack ventilation does not depend on the direction of wind (Santamouris, 2005).

The limitation of stack ventilation it is difficult to control air movement inside the building and air velocity is small. With this principle it is possible to achieve healthy and quality air inside a building as well as favourable airflow for occupants in a building if the difference between the temperature inside the building and surrounding air temperature lie within a satisfactory range. However, stack ventilation principle cannot enhance thermal comfort in areas with hot and humid conditions.

2.3.5 Section conclusions

An objective of this work is to create an effective natural ventilation mechanism that provides building occupants (students, staff) comfort and creates the physiological cooling response. This achieved through air flow with high speed (ms^{-1}) as opposed to high volume rate (ls^{-1} or m^3s^{-1}) or mass flow rate (kgs^{-1}). Therefore, natural ventilation with wind force as the dominant force is the most preferred.

The three main functions of building ventilation are to supply healthy and quality air, enhance human comfort inside buildings and cool building structures. Ventilation systems can either natural or mechanical.

Naturally driven ventilation systems are preferred because they offer high quality indoor environment, are preferred by building occupants and they consume lower energy that their mechanical counterparts. Naturally driven ventilation systems use naturally created pressure difference resulting from stack and/or wind forces to force air in and out of a building. Ventilation due to wind force, pushes warmer air up and pulls in colder air from outside into the lower part of the building while ventilation due to stack force while ventilation due to wind force forces air to the building's suction zone from the building's pressure zone. In reality these two forces act in combination and may reinforce each or cancel each other out. If the dominant force is wind, the velocity of air flow in the building is higher. It is difficult to control air movement due to stack force because of its rather small inertia force and it produces a lower air velocity. It is therefore recommended that buildings found in hot and humid areas implement cross ventilation to enhance indoor comfort. This is wind is the dominant force in cross ventilation wind and it produces higher air velocity inside the building that creates a physiological cooling effect. Induced natural ventilation strategies can be implemented in cases where cross ventilation mechanism is not practically possible.

2.4 Induced Natural ventilation in buildings

Hot and humid climatic areas are characterized mainly by high temperatures, low average windspeeds, small diurnal atmospheric temperature ranges all through the year, where the monthly variation in average temperatures lies within 5°C (Givoni, 1969; Szokolay, 2004). In such climatic areas there are two main strategies necessary for enhancing thermal conditions inside a building or any indoor space (i) To prevent air temperatures indoor from increasing when it is hot and (ii) Ensuring continuous high velocity air flow to create a cooling end result (Givoni, 1969; Lei, 2009). There are cases when the implementation of the basic principles of natural ventilation; stack, cross and single-sided ventilation is not possible or is not sufficient enough to give the needed continuous and high-speed air movement. In such cases other strategies may be added to enhance natural ventilation and improve indoor comfort. Induced natural ventilation strategies covered in the following section include solar ventilation, wing-walls and wind towers. These strategies are discussed and analysed so as to clearly understand induced ventilation strategies that can be used to improve indoor comfort in hot and humid climatic condition in order realize the objective of this study.

2.4.1 Wind towers

For centuries traditional passive cooling wind towers have been employed in hot areas in Eastern Asia and Middle East (Ghiaus and Allard, 2012). In some literature this strategy is also known as wind catcher since it catches cooler air from outside a building from a higher elevation and forces it downwards into an indoor space, and it is wind driven. In this strategy a vertical shaft of height ranging between 2m and 20m above the roof level of a building is utilized with openings at the building level and its peak (Bahadori, 1994). Therefore, the shaft connects an indoor space to the outside environment. Traditional wind tower systems used both stack and wind forces to capture fresher air with minimal dust at high momentum from the ground and force it into an indoor space.

This strategy is proposed as appropriate for hot and arid climatic regions that experience high daily temperature variation; high temperatures during the day and low temperatures at night (Bansal, Hauser and Minke, 1994). This strategy is also suitable for building in densely populated areas with buildings closely located and where it is difficult to have extra openings in a building space. A downward current is created in the morning when the walls of the towers are still cool from the coolness stored during the night (reverse stack effect). Cooler air from outside is forced inside a building via the opened located at the top of the inlet shaft, moves down and circulates the building space. Air is then expelled via the building outlet openings that may be found in the tower or may be positioned at the building level to promote air circulation in the building space (Bansal, Hauser and Minke, 1994; Khan, Su and Riffat, 2008); Figure 2-14 (a) illustrates this.

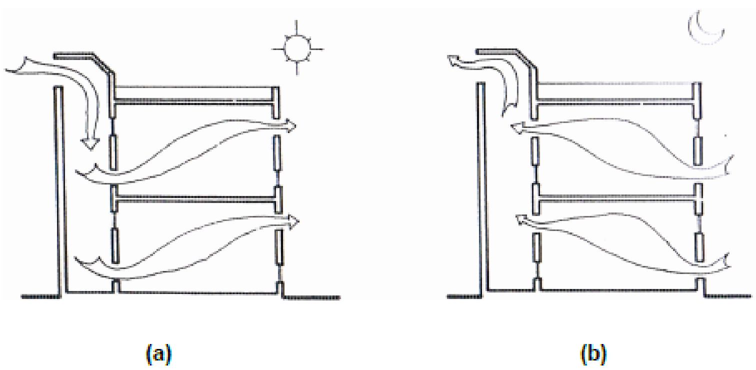


Figure 2-14 - wind tower system principles: (a) daytime down-draught operating principles; (b) night-time up-draught reverse-up (Bansal, Hauser and Minke, 1994).

Reverse air flow occurs at night. The tower and the now warm walls heat indoor air which is pushed up to the tower by buoyancy and an upward current is created (Allard, 1998) and expelled via the top openings in the tower which now serve as outlets (Bansal, Hauser and

Minke, 1994) ; this is illustrated in Figure 2-14(b). When an upward current is created, wind tower serves as an extractor; it expels the relatively hot air out to the surrounding which is suitable for warm and humid areas (Gonzelez-Trevizo *et al.*, 2013). It is however important to make sure that the temperature of surrounding does not rise above 37°C.

Factors that influence the performance of wind-towers include: i) wind angle of incidence at the openings Khan, Su and Riffat, (2008); ii) location and size of the openings (Ghiaus and Allard, 2005); and finally iii) the geometry of the tower; its height, shape and cross-sectional area (Bouchahm, Bourbia and Balhamri, 2011; Ghadiri, Ibrahim and Mohamed, 2014). For better performance it is proposed to have the inlet on the windward side and the outlet on the leeward side of the building so as benefit from the extra effects of wind caused by the high differences in pressure across the inlet and outlet (Allard, 1998). It is also advisable to have high tower openings to maintain high wind pressure at the inlet and to ensure that the ventilation system is unaffected by the direction of prevailing wind (Bansal, Hauser and Minke, 1994; Ghiaus and Allard, 2012).

Nevertheless, the construction and maintenance of the conventional wind-tower system is costly. It is also difficult to control the quantity and quality of air intake due to short circuiting which may happen when air flows into the tower and directly out through another opening in the tower. Hence traditional wind towers are not suitable for areas with low wind velocities typically for areas with average wind velocities below $4ms^{-1}$ (Bahadori, 1994; Bahadori, Mazidi and Dehghani, 2008). Additionally, stack and wind forces may act against each other resulting in much lower indoor air velocities. Consequently, advanced wind-tower designs have been recommended.

These advanced wind-towers that are incorporated with other leading technologies and systems are very efficient in providing human comfort in buildings (Khan, Su and Riffat, 2008). For instance, automated control dampers are used to prevent short circuiting in the two with multiple tower openings. Additionally modern advanced wind towers may include; i) evaporative coolers like evaporative cooler pads at the tower top, wetted surfaces and columns in the tower (Bahadori, 1994; Bahadori, Mazidi and Dehghani, 2008) , and at the bottom a pool (Bouchahm, Bourbia and Balhamri, 2011) intended to lower the temperature of indoor air and to raise the relative humidity of indoor air especially in hot areas; ii) solar chimneys or collectors (Hughes, Calautit and Ghani, 2012), that enhance ventilation due to stack effect during periods of low winds; iii) additional devices to draw in and draw out air to induce air velocity indoors for example fans powered by photovoltaic modules (Hughes, Calautit and Ghani, 2012).

Additionally, wind towers can redesign. For example wind towers with disc shaped roofs make use of a conventional wind-tower with a shaped-roof top as shown in Figure 2-15 (Blocken *et al.*, 2011; Sadafi *et al.*, 2011). The Bernoulli effect is created by these roofs; positive pressure is created above the roof and negative pressure is created below the roof resulting in air from the surrounding being pulled out of the building via top tower openings as illustrated in Figure 2-15 (a). Consequently, regardless of the high difference in pressure between the inlet opening and the outlet opening there will a high indoor air movement.

(a) **(b)** **(c)**

Figure 2-15 - (Venturi-shaped and disc-shaped roof) wind tower: (a) the Bernoulli Effect; (b) venturi-shaped roof house (Haw et al. 2012); (c) Disc shaped roof reduce scale building Blocken et al., 2011.

Several experimental studies have reviewed the effectiveness of wind-tower strategy with roof designs and the results showed that the design was effective at inducing indoor air movement (Blocken *et al.*, 2011; Sadafi *et al.*, 2011; van Hooff *et al.*, 2011). In addition Sadafi *et al.*, (2011) investigated the performance of wind tower strategy using Venturi-shaped roof in Malaysia, a hot and humid climate; they found that the system effectively induced air change rate and extraction flow rate in the room used for the experiment; illustrated in Figure 2-15 (b). The wind-tower strategy using Venturi-shaped roof had higher air changes per hour compared to wind-tower design only at the same prevailing wind speed which had air changes rate of 20ACH (Bahadori, 1994; Bansal, Hauser and Minke, 1994).

Even though conventional wind towers use both stack and wind forces, they are proposed for use in hot climatic regions with high diurnal range of temperature but are not suited for areas where the average surround wind velocities are below $4ms^{-1}$. Therefore, this strategy is not suitable in areas with hot and humid climatic conditions characterized by low surrounding wind speeds and low diurnal range of temperature. As the average wind speed in Kuwait is approximately $5ms^{-1}$, this concept of raising negative pressure and hence the difference in pressure between a building's inlet opening and outlet opening beneath the disc-shaped roof or Venturi-shaped roof is intriguing since it is capable of inducing indoor airflow rate in buildings in hot and humid areas.

2.4.2 Solar ventilation strategies

These are natural indoor ventilation strategies that use stack force caused by solar heating. Solar ventilation concept has been employed in building for many years in different climatic regions among them hot and humid regions. When it is hot and windless stack and wind forces are not strong and sufficient enough to bring about the needed air flow in a building, special design elements are incorporated in buildings such as solar chimneys, solar walls and double skin or ventilated exteriors may be used to maximize the difference between indoor and outdoor temperature hence create the effect of stack force (Bansal, Hauser and Minke, 1994; Khanal and Lei, 2011). Solar ventilation makes use of a chimney or a vertical or inclined channel with two panels separated by an air gap. These panels are: i) a solar collector, storage wall also known as solar wall to increase the effectiveness of absorbing solar radiation reaching the surface or absorptance and reduce the release of solar radiation that has been absorbed or emittance; and ii) a high solar transmittance clear cover to increase solar gain (Zhai, Song and Wang, 2011).

Stack force is the main mechanism that causes air movement (Gan, 2006). Solar heat absorbed and stored by the solar walls heats the air inside the channel; the heated air then rises up and gets expelled via the outlet opening at the top of the chimney. It should however be noted that induced stack ventilation differs from normal stack ventilation that occurs due to temperature differences inside a building and the surrounding. Usually it is favourable to maintain air temperature indoors as low as possible to prevent overheating and ensure human comfort. Contrarily solar ventilation mechanisms are particular designed to store heat; to enhance indoor ventilation and prevent thermal discomfort, these systems are kept in isolation from the space occupied by people (Bansal et al., 1994a). Depending on the specific characteristics of a system, solar ventilation mechanisms can be used insulation, ventilation or even heating (Zalewski *et al.*, 2002; Chow *et al.*, 2010; Zhai, Song and Wang, 2011) as illustrated in Figure 2-16. Insulating and heating techniques are not within the subject of this research and therefore only natural solar ventilation techniques will be covered.

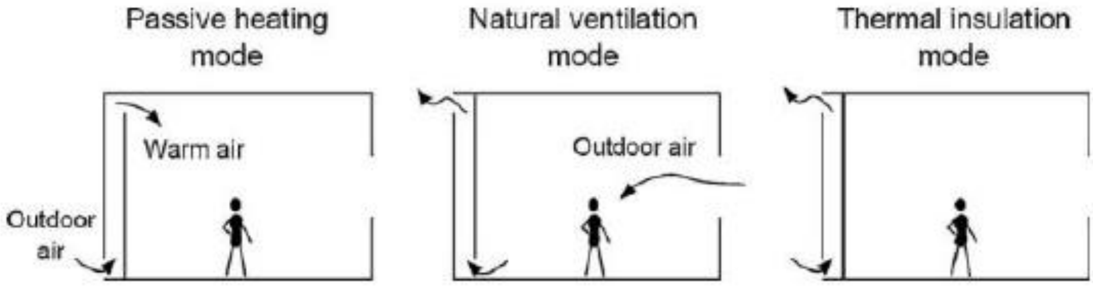


Figure 2-16 - Solar ventilation strategies different modes (Chow *et al.*, 2010).

2.4.3 Wind catchers

A wind catcher uses passive stack ventilation principles to extract air from an indoor space and the wind tower concept for air supply. Wind catcher systems have been used in Middle East countries for over 3,000 years Figure 2-17 (Bahadori, 1994).

Traditionally, wind catcher systems were made from wood-reinforced masonry and openings were positioned at heights of about 2 to 20 meters above building level; taller towers captured higher wind velocities and low amounts of sand (Bahadori, 1994; Bahadori, Mazidi and Dehghani, 2008). Wind catcher systems are natural ventilation mechanisms that employ passive cooling principles to create indoor thermal comfort hence their applicability in hot and arid climatic regions like the Middle East (Karakatsanis, Bahadori and Vickery, 1986). These systems are conventionally employed in high-density urban areas where adjacent buildings hinder free flow of air (Sharag-Eldin, 1994).

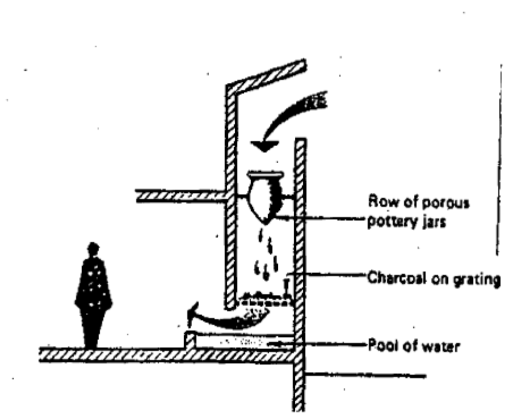


Figure 2-17 - Wind catcher system used in Middle East Countries (Arabian Gulf Countries) (Bahadori, 1994).

Additionally, traditional wind catchers are beautiful and appealing to the eye; and can be added to architectural designs and are essentially long-lasting (Gallo, 1996; Gage and Graham, 2000).

Some Roman paintings from around 10 BC illustrate the usage of wind catcher systems; the structures were characteristically found to be Egyptian (Knauer, 1990). With a wind catcher system, there is no need to have separate inlet openings; this makes them suitable for diverse applications that would normally need mechanical ventilation for an effective rate of air exchange shown in Figure 2-18 (Steemers, Lewis and Goulding, 1992). During night-time when it is not windy, they function in the same way as a chimney. The heat absorbed and stored in the building material is extracted by an up draught and fresh cool air from outside enters the building (Yaghoubi, Sabzevari and Golneshan, 1991).

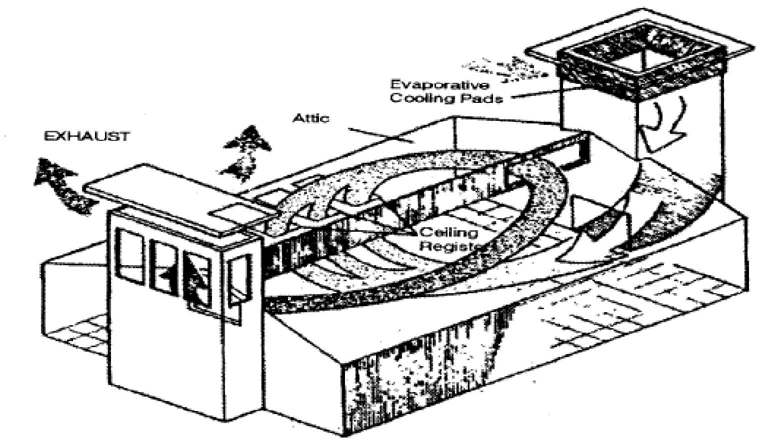


Figure 2-18 - Wind Catcher System (Steemers, Lewis and Goulding, 1992).

Modern wind catcher designs combine both the passive stack principle and the wind tower principle. The stack is separated into two or into four; the division runs the entire stack length as illustrated in the Figure 2-19 below.

Figure 2-19 - Sharjah, UAE Modern Wind Catcher (Elmualim 2000).

The modern wind catcher design uses the stack to connect the indoor space that requires ventilation to the external environment. In this modern system, air movement is confined to the building roof by the inflow of air through the system's windward side. This air makes a 90°turn, wind pressure then pushes the air down to the indoor space below. Incoming fresh, cool air from outside replaces the warm, stuffy air inside which is pushed up by stack effect and forced out through the system's leeward side. The functions of the stack halves or quadrants change as the direction of wind changes (Elmualim and Awbi, 2001). Usually, air flowing into the wind catcher system passes through one of the halves or two of the quadrants. The remaining half or quadrants are positioned on the system's leeward side and are passive. Therefore the wind catcher system is able to operate irrespective of the direction of the wind (Bahadori, 1994; Elmualim and Awbi, 2001; Awbi, 2013). The wind catcher system does not have any moving parts and hence it does not require maintenance. Its major advantage is that air is supplied at the roof level and this air is usually cleaner compared to air supply at the ground level; this makes the system suitable especially for urban areas where buildings are near roads (Sharag-Eldin, 1994).

Nowadays engineers and architects are increasingly including wind catcher systems in building designs UK. There are very many companies in the UK that design and install wind catcher systems. Figure 2-20 illustrate wind catcher installation designs in UK (Loncour *et al.*, 2000).

Figure 2-20 - Installation of different types of Modern Wind-Catcher (Loncour *et al.*, 2000)

Most modern wind catcher installations are terminated at the building ceiling and usually, the stack consists of four quadrants: two quadrants supply air into the indoor space and the other two quadrants extract air from the space. Nevertheless, there are some wind catchers designs that are terminated at levels higher than the ceiling while the quadrants for air supply and extraction are separated by flexi-duct that serve the spaces that require ventilation as illustrated in Figure 2-21. (PASSIVENT, 2001).

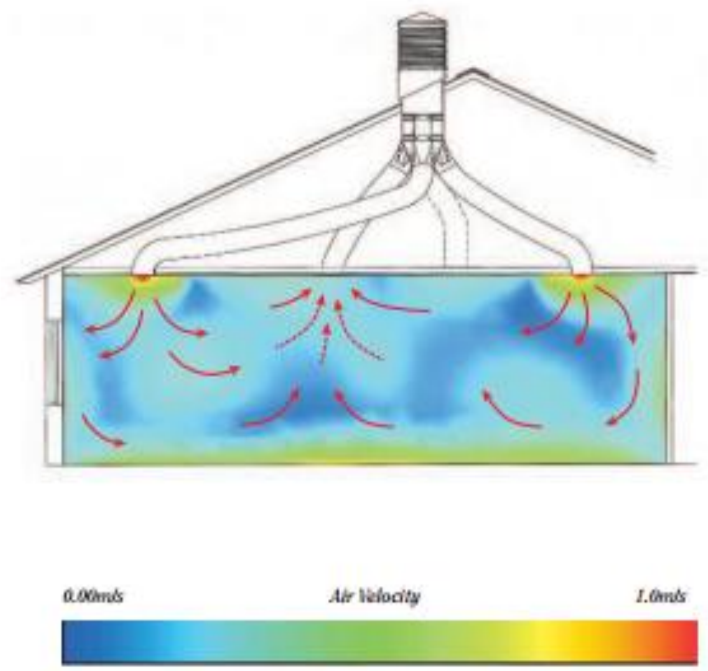


Figure 2-21 - Modern Wind catcher air supply and extract (Passivent 2001).

2.4.4 Current practices and studies regarding wind catcher system

Recently, several buildings designed to incorporate wind catchers have attracted a lot of attention; The Jubilee Campus at Nottingham University has a revolving cowl that removes hot, stale air from internal spaces of the building; this is similar to a mushroom wind catcher system used at the Inland Revenue building in Nottingham (Hurdle, 2001).

Most research studies on the use of wind catcher systems have been conducted in relation to hot and arid climatic regions like the Middle East; less has been done on the application of wind catchers in temperate climatic regions like the UK. Bahadori (1994) highlights that wind catcher systems are beneficial because they do not consume energy. Wind catchers using passive cooling techniques to naturally cool buildings; cooling occurs due to buoyancy or wind effect and traditionally due to evaporative effects when air passes over a wet surface.

Wind catchers have some disadvantages as well; for instance, dust, sand, tiny birds, insects and other airborne pollution get into the building. Also, some amount of air drawn into the wind catcher system escapes through the opening of the system and does not reach the space requiring ventilation. For a wind catcher system with a single vent that faces the direction of prevailing wind, air that is drawn into the wind catcher also gets into the building. The wind catcher system can only store a small amount of cool air. Wind catchers were found to be ineffective in regions with low prevailing wind speeds while conventional wind catcher designs that employ evaporative cooling had limited application (Karakatsanis, Bahadori and Vickery, 1986). Bahadori (1994) conducted a wind tunnel test on a small scale. He indicated it is important to understand the air-flow surrounding a building and the building's envelope pressure distribution in order to approximate natural ventilation potential in the building's internal space (Karakatsanis, Bahadori and Vickery, 1986) .

Karakatsanis et al., (1986) also conducted a wind tunnel test on a limited scope for a wind tower linked to a building with a courtyard and examined the coefficients of pressure distribution. The researchers established that the rate at which air flows into the building from the system is dependent on the coefficients of pressure at the building's openings. Covering the opening reduces pressure coefficient resulting in an increased rate of air flow into the building. The damping technique employed in wind towers reduces the rate of air flow. Sometimes the wind catcher functioned like a suction device, but this was dependent on the angle of the prevailing wind and the design of the courtyard. The researchers further indicated that the rate of air flow could be augmented by stopping air from escaping through the openings on the leeward side of the system which is essentially is short-circuiting.

Nevertheless, the studies based on the wind tunnel tests could not be corroborated in real buildings with wind catcher systems. It is important to carry out post-occupancy assessment studies where it is possible to accurately measure indoor air parameters and evaluate the human comfort.

Sensitivity analysis indicated that wind direction has minimal effect on the performance of wind catchers compared to base models. Nevertheless, different wind catcher configurations behaved differently depending on the height of the system, where the system is located in a building and also the characteristics of the buildings adjacent to the building requiring ventilation. This finding to some extent differs with other publications (Elmualim and Awbi, 2001; Kolokotroni, Ayiomamitis and Ge, 2002) that clearly indicated that the performance of a wind catcher system is dependent on the direction and speed of the wind. To achieve a maximum rate of air flow, the focus should be on the cowl design and the connection between the openings. The wind catcher design that has only one opening that faces the direction of the wind was found to have the best performance. Including filters and moist pads to cool the spaces increased obstructed air flow into the indoor space and hence decreased indoor air flow rates.

In situations like this, it would be best use higher wind catcher systems facing away and this produces upward flow due to negative pressure from the direction of the wind (Sharag-Eldin, 1994). Hines et. al., (1994) analysed thermal storage in square shaped wind catchers. The researchers found out that increasing mass inside the wall of the tower had minimal effect on the performance of the wind tower. However, it is effective and cheap to use the traditional cooling walls technique inside the tower walls.

Battle et. al., (2000) conducted several small-scale tests in a boundary layer wind tunnel laboratory using different wind catcher configurations. The researchers found that when the wind blows at 0° relative to inlet, it creates higher wind pressure at inlet segments and lower wind pressure at outlet segments. The opposite happens when the wind blows at 45°. The inlet segment is slightly effective whilst the extract segment operates more efficiently. Wind catcher system's performance is therefore affected more by the angle at which the wind is blowing; its effectiveness increases as the system moves towards the direct wind direction (Battle, Zanchetta and Heath, 2000; Elmualim and Awbi, 2001).

Gage and Graham (2000) carried out a study to investigate the performance of a four and six segment wind catcher systems in a small scope wind tunnel model. The study revealed that a 4-segment wind catcher system having a 45° orientation generated the highest differences in pressure between the supply segments and extract segments, therefore producing the highest air velocities in the duct.

Bansal et al (1994) carried out a study to investigate induced natural ventilation a solar chimney- wind tower combination. The researchers indicated that a solar chimney- wind tower combination created a remarkable system that can be integrated into buildings to deliver natural ventilation.

Two researchers carried out a CFD simulation to investigate how wind catcher systems performed in hot climatic regions. The study revealed that wind catchers can be employed in such regions to facilitate ventilation during the night (Aboulnaga, 1998). However, the researchers did not provide information regarding the CFD codes used, boundary conditions or computer requirements. Nevertheless, CFD is a popular tool used in the design and analysis of air movement in indoor spaces (Anderson, 1995; Al., 2003). Harris and Webb (1996) carried out a small scope wind tunnel test to investigate the application of wind catcher systems; the researchers measured air movement using an anemometer, used coloured dyes for flume tests and the sulphur hexafluoride (SF_6) tracer gas method to measure ventilation rates. Wind velocities of 5 m/s produced ventilation rates of over 6 ac/h while wind velocities of 3 m/s produced ventilation rates of 2.5 ac/h. The test room had an area of 15 m^2 and the wind catcher had an area of 0.0729 m^2 (Harris and Webb, 1996). The findings indicate inconsistencies between the approaches the researchers employed.

A number of studies to investigate the performance of wind catchers in actual buildings was have been conducted for commercial use. Researchers conducted a tracer gas analysis test on the Building Research Establishment (BRE) office of the Future (Riain *et al.*, 1999). A study was conducted in hot climatic regions to investigate thermal performance in three public establishments that are naturally ventilated using wind towers. The study established the effectiveness of wind towers in improving air circulation inside building spaces (Yaghoubi, Sabzevari and Golneshan, 1991). Farija (1997) carried out studies to investigate the performance of wind catchers in houses in hot and arid areas. Nevertheless, their findings were inadequate and could not justify the potential and applicability of wind catchers in temperate regions like the UK.

2.4.5 Section summary

Implementation of natural ventilation mechanisms to improve human comfort indoors is quite challenging especially in hot climatic regions because of high surrounding temperatures, low speeds of external wind and low diurnal ranges of temperature. Additionally, natural ventilation mechanisms are variable. Nevertheless, natural ventilation mechanisms have become a centre of attention for several researchers since most building occupants prefer natural ventilation mechanisms compared to mechanical ones. Also, natural ventilation systems consume relatively less energy and provide excellent indoor air quality.

This section analysed a number of natural ventilation mechanisms used in hot and humid climatic regions to enhance indoor thermal comfort. These mechanisms include wind towers, wing walls and finally solar ventilation mechanisms such as solar chimneys, solar walls and double-skin facades. All this is in bid to determine existing knowledge to assist in the design of a natural ventilation mechanism for a classroom that has single-sided ventilation in Kuwait. From the literature it is clear that wind-based ventilation strategies such as wing walls and new advanced wind towers coupled with shaped roofs are capable of effectively producing high velocity indoor air movement that is necessary for producing a cooling effect and thus indoor thermal comfort in hot areas. Typically, Kuwait experiences wind speeds ranging from 9 ms^{-1} to 14 ms^{-1}; wind catcher strategy is expected to produce average indoor air velocities ranging from $0.4ms^{-1}$to $4.6ms^{-1}$. In comparison stack-based mechanisms such as solar ventilation produces low average indoor air velocities typically lower than $0.25ms^{-1}$. Even though stack-based mechanisms are capable of offering quality indoor atmosphere, they are incapable of providing thermal comfort indoors especially in hot areas.

From the analysis, it can be pointed out that wind based natural ventilation strategies are the most suitable for buildings found in hot and humid climatic countries such as Kuwait; this in comparison with stack-based strategies. Natural ventilation strategies based on wind force provide uniformly distributed and controllable indoor air movement with high average velocity necessary in creating a cooling effect and hence human comfort indoors. The following sections provide a description of how increased air velocity impact physiological cooling, and the limits of increased indoor air velocity to achieve thermal comfort at higher indoor air temperatures.

2.5 Evaporative Cooling

Evaporation is a process that occurs constantly. Perspiration or sweat can be taken as the most basic example in which the body cools itself by excreting it. People tend to sweat more in hot days and during humidity because the amount of heat transfer depends solely upon the rate of evaporation. This evaporation rate, in fact is determined by the temperature of air and the humidity as well.

A phenomenon that involves the evaporation of a liquid, generally in the nearby air and cools a liquid or an object that is in contact with it is known as evaporative cooling. The amount of heat that is required to evaporate a liquid is called Latent heat. This type of heat occurs from the surrounding gas and surfaces and the liquid itself. The comparison of the wet-bulb temperature with the air’s dry-bulb temperature serves as a measure of the potential for evaporative cooling when taking into account the evaporation of water into air. The difference between the two temperatures increases the evaporative cooling effect. No net evaporation of water into air happens when the two temperatures are equal. Thus producing no cooling effect at all.

Commonly, evaporative cooling is used to obtain thermal comfort by cooling buildings as it consumes less energy than many cooling forms and is comparatively less expensive. A downside can be that evaporative cooling needs large supply of water as a source for evaporation. However, the water evaporate can increase humidity that can cause serious health concerns, such as the risk of Legionalla. In addition, for the geographic locations where humidity is high, or if the humidity is high at a certain time of the year, the evaporative cooling process will be ineffective. Hence it is important to keep these limitations of evaporative cooling in mind before suggesting it as a cooling technology. In the case of Kuwait, it is a hot and dry climate, thus making evaporative cooling a suitable technology to be considered.

2.5.1 Evaporative coolers

A device that uses simply the evaporation of water into air is known as an evaporative cooler. These are different from absorption air conditioning or refrigeration that use absorption refrigeration cycles or vapour compression. It is specifically well suited for climates where the humidity is less, and the air is hot. The operating and installation cost of an evaporative cooler can be less than the refrigerative air conditioning in climates that are dry. In order to get optimal performance, vapour compression and evaporative cooling are sometimes used as a combination. Evaporative cooling may have less thermal comfort use beyond the increased air movements and ventilation it supplies in climates where the humidity is high.

Figure 2-22 demonstrates a classic industrial and residential evaporative cooler that can be categorized as a plastic box with vented sides or an enclosed metal comprising of a water pump that is used to evaporate the wet cooling pads, an electric motor and a 'blower' or a centrifugal fan. These units can be arranged on the windows (horizontal flow or side draft) or exterior walls or on the roof (down flow or down draft) of buildings. The fan extracts atmospheric air through the damp pads and through the vents on the sides of the unit for cooling. The water from the pads is evaporated by the heat in the air, this way the pads remain consistently re-damped so as to continue the cooling process. In this way, through a vent in the wall or the roof, the cooled and moist air is transported to the building. Factors affecting the evaporation rate are air pressure, evaporation surface area, air movement, air temperature and relative humidity.

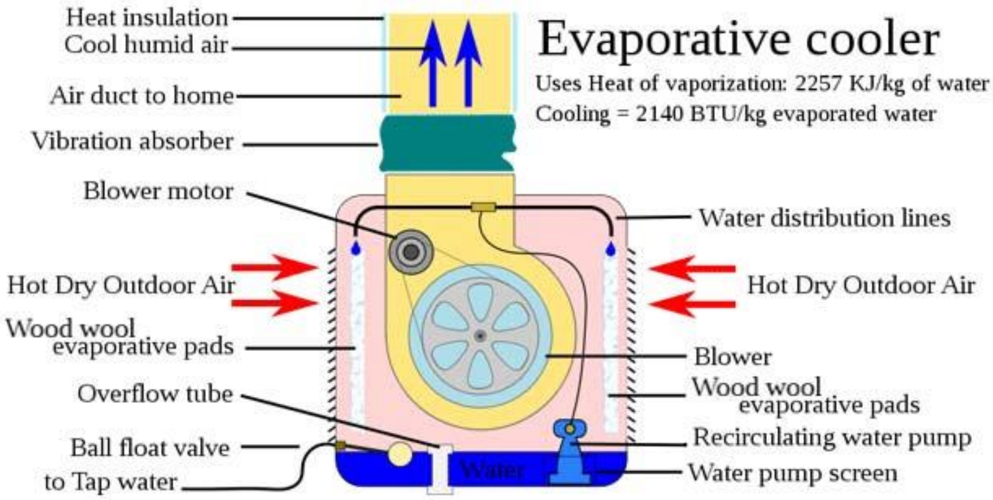


Figure 2-22: an illustration for Evaporative cooler device (Dilmen, 2020).

Air pressure dictates the rate of molecules of water that will eventually diffuse away from the surface. The diffusion process speeds up due to low air pressure whereas high air pressure would slow it down. More energy is needed under high pressures (for example at sea level as compared to high altitudes), in order to increase the speed of molecules of water so that they can escape as the water molecules near the surface are squeezed by the atmospheric pressure.

Evaporation surface area is proportional to the evaporation rate, as a greater surface area permits more atoms or molecules to come in contact with air and evacuate the liquid. For example, the water that is spilled over the table will take less time to evaporate as compared to the same amount of water that is left in a cup.

Air movements of an electric fan or natural wind is a crucial factor that affects the rate of evaporation, as through this process, humid air is replaced by less humid air above the wet surface. The evaporation rate is maintained as well as increased by this process.

Higher Air temperatures is proportional to the rate of evaporation and depends on humidity and air speed. This happens because water vapour atoms or molecules have a higher average speed at higher temperatures, and this allows more particles to burst away from the surface of liquid. As an example, a street that is wet will evidently dry faster in the sun than in the shade, with all other factors remaining the same.

Relative humidity is the water content in the air as a percentage of the highest quantity of water vapour that the air has the capability to hold at some specific temperature. The absolute amount of water vapour present in air is referred to as the humidity of air. The evaporative cooling is not as effective in the situations where there is higher relative humidity.

2.5.2 Evaporative cooler designs

There are a few categories for the evaporative coolers, such as two stage or indirect-direct evaporative cooling, indirect evaporative cooling and direct evaporative cooling that are now briefly described.

Direct evaporative cooling (open circuit) is used to lower the air temperature directly by utilizing latent heat of evaporation because the water is changed into vapour. By using the heat present in the air to evaporate water in this process, the dry and warm air is transformed into moist and cool air. The outside air is cooled by evaporation and blown through a water saturated medium with direct evaporative cooling.

Until the air stream is near saturation, moisture is instilled into the air stream by the directive evaporative cooling. The dry bulb temperature of the air is decreased during this process. Evidently, the moisture content of the air is enhanced during this process. Thus, this is known as direct evaporative cooling. There are numerous applications for directive evaporative cooling. For instance, PDEC (the passive downdraught evaporative cooling) has been used in Middle East and Turkey for centuries, and since the energy crises in the seventies this has been a topic of high interest worldwide (Wachenfeldt, Bell and Forskningsråd, 2003). As indicated by (Cunningham and Thompson, 1986), an experimental building in Tuscon, Italy. In order to drive a significant air flow, a downdraught tower including wetted cellulose pads is installed.

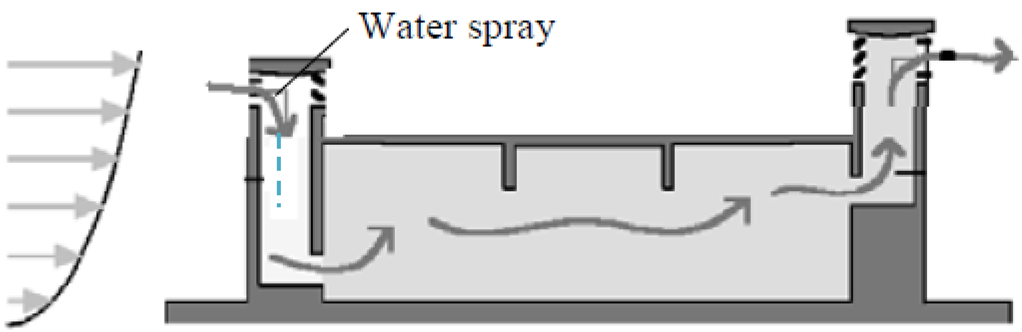


Figure 2-23 - A diagram illustrating passive downdraught evaporative cooling (PDEC). (Adapted from (Wachenfeldt, Bell and Forskningsråd, 2003)*).*

As shown in the Figure 2-23, there are multiple towers in the building illustrated in the figure. The towers are equipped with a water/vapour supply, these supplies are located at the top. While maintaining conditions near saturation along its entire length, consistent droplets of water fall down through the tower. The cool air then departs its base and descends the tower. Here, it is transported to the adjacent spaces.

With successive differences in the density of air and within a local thermal imbalance, in this process, water is transformed into gas from a state of liquid. Consequently, the air moves from the top of the tower, i.e. the high-pressure zone where the air is less dense and hot to the bottom of the tower, i.e. in a lower pressure zone where the air is denser and colder.

The passive downdraught evaporative cooling is specifically utilized in dry and hot climates. It has numerous benefits such as it can be easily adapted to an existing and new constructions because it is flexible. It is an adiabatic process as there is no extraction or addition of energy (heat) from the system and evidently, it can be utterly passive. It supplies atmospheric air with moisture raising the levels of RH and in turn improves the thermal comfort. The existing fabric limitations such as envelope material and architectural forms make PDEC dependent on it, in addition PDEC is also dependent on the power of required cooling.

For example, discomfort can be induced when a shower system needs to be placed at a low height PDEC based upon free convection. The non-evaporated water droplets may wet the people. The time duration before the water droplets reaches the ground is increased by the inclusion of a fan. This helps them to evaporate completely and evidently switch to a mechanical mode from downdraught passive one. Thus, it becomes a hybrid system.

The energy consumption rate is low enough to warrant its application to an existing fabric even on a mechanical or hybrid DEC system, while energy savings are really high. There are many advantages of cooling buildings in this way, as opposed to air conditioning. Firstly, there is elimination of refrigerant, maintenance and energy costs and lower capital. This system can also provide an economical advantage. However, there are architectural implications to the utilization of PDEC. Other methods of evaporative cooling are indirect evaporative cooling (IEC) and direct-indirect evaporative cooling (DIEC) – however they have not been used in this current work.

2.6 Literature review conclusions:

In this chapter, a thorough background to the topics and systems involved in this project were reviewed. First, the concept of thermal comfort, its application to hot and humid climates, and specifically to classrooms around the world, and also in hot climates such as in Kuwait were described, with the limitations highlighted. Following this, based on scarce literature available on thermal comfort and indoor air quality in Kuwaiti classrooms, the issue of poor indoor air quality because of adhering to thermal comfort standards in classrooms in peak summer conditions was highlighted. As increased air exchange helps this problem Increased air velocity to improve thermal comfort was described in detail. International recommendations such as ASHRAE has proposed an upper acceptable air velocity limit of $0.8ms^{-1}$; which means air speeds higher than this may cause discomfort because of cool draught effect. Several studies have shown that the recommendation by ASHRAE to be extremely restrictive particularly for tropical areas; in the case of this study classroom buildings. These studies have shown that in hot and humid areas, air speeds of up to 3 ms^{-1} and even 4 ms^{-1} are suitable in some cases to enhance and create comfort in naturally ventilated buildings. These findings were kept in view when conducting the modelling and simulation work. As this appeared to be a promising avenue, natural ventilations systems were reviewed which culminated in the identification of the wind-catcher systems together with evaporative cooling as promising designs to achieve this project’s goals.

In summary the following observations have been identified through review of literature:

1. To the authors knowledge, there are an inadequate number of studies that analyse thermal comfort for classrooms in Kuwait.
2. The thermal comfort indicators used for assessment of educational establishment utilised tabulated data based on adults, while they are applied to children in classrooms.
3. Increased air velocity in hot and dry climates broadens the range of comfortable indoor air temperature. There are several studies that highlight this fact, and it is supported by ample literature. However, current ASHREA standards on limits to acceptable air speed are highly restrictive for application in hot and dry climates; this has been documented in several studies.
4. Natural ventilation strategies can help provide increased air speed within the building to provide improved thermal comfort to the classroom’s occupants, whilst improving indoor air quality in an energy efficient manner.
5. The wind catcher system is a promising natural ventilation strategy for application in hot and dry climates.

6. Evaporative cooling, in addition to wind-catchers may deliver improved thermal comfort at lower energy demand in classrooms, within the hot and dry climate of Kuwait.

In view of the above observations made through the review of literature, the following main research aim is defined for this project as follows:

"To develop a natural ventilation-based strategy/design for classrooms in the hot and dry climate of Kuwait, to provide satisfactory thermal comfort at improved indoor air quality in an energy efficient manner"

Chapter 3 – Methodology

In this section, the overall research methodology used in this project is described. First an overview of the different research methods is provided, followed by elaborating on the specific research methodology selected for this project.

3.1 Research methods overview

Research in principle is designed to answer questions for which answers are sought. This process can be divided in the stage: problem, hypothesis, research design, measurement, data collection, data analysis and generalization (Blaxter, L., Hughes, C., Tight, 2006). Additionally, this is not a linear process, rather the ending of cycle leads to further questions that may be investigated further.

In particular, the research of a project reflects the approach and worldview of the researcher, strategies of inquiry and provides information on the specific methods employed (Creswell, 2009). Creswell (Creswell, 2009) further provide information on the four worldview that a researcher may adopt, namely post positivism, constructivism, advocacy/participatory and pragmatism. Among these, when the solution to a real-world problem is sought, that is associated with real world constraints in time and resources, pragmatism offers and approach that is problem oriented. Consequently, many research projects within the building energy domain adopt this worldview as evident from a ample literature (Georgiou, 2015; Duran, 2019; Sadr, 2019). Considering that this approach is well suited for this current project as well, it is also employed here as opposed to the other three.

Decisions on the selection of specific methods in the research methodology depend on the nature of the problem being tackled. Broadly, they are classified into qualitative and quantitative methods. (Davies, 2015) provides a summary in terms of the characteristics of the two approaches, which is an aid in selecting the correct research method for the respective stage of research. Quantitate data appears as numbers, the nature of which is hard, reliable and objective. Whereas, qualitative data can take the form of transcribed interviews and textual information that may be subjective, rich and deep. There is no one methods that takes precedence over the other, rather it is the appropriately to the problem and the designed solution at hand, that is the criteria for selecting the research method. as this current project's aim is to quantify with hard number the impact of a newly devised natural ventilation strategy in Kuwaiti school buildings, quantitative methods are used in this project. The following section details stepwise the research design and the research methods and tools employed to fulfil the project objectives. As this current project involves the evaluation of a novel building design and is to be assessed using quantitative data generated from computer simulations, this thesis adopts a quantitative research method approach which is detailed in the sections that follow.

Table 3-1 - Quantitative and Qualitative research methods (Davies 2016)

Quantitative Research Method	**Qualitative Research Method**
- Data takes the form of counts, correlations and other statistical formulae; - Methods are perceived as 'data condensers' - Commonly used to study limited characteristics of many examples of something (more than 50); - Emphasises the parsimony of accounts; - Quantitative researchers adopt objective stance; - Focuses on variables and converts them into specific actions during planning stage that occurs before and disconnect from gathering or analysing data; - Quantitative researchers develop techniques to produce data to nurture the transformation from abstract ideas to detailed data collection techniques to exact numerical information; - Quantitative researchers deliberate and reflect on concepts before they gather data; - Research upholds a preparatory role; - Relationship between researcher and subject is distant; - Researcher's stance is as an outsider; - Confirming relationship between theory and research; - Research strategy is structured; - Scope of findings is nomothetic; - Image of social reality is static and external to actor; - Nature of data is hard and reliable.	- Data takes the form of words, images and narratives of all kinds. - Methods are perceived as 'data enhancers' - Commonly used to study multiple characteristics of a few examples (less than 50); - Emphasises the richness of accounts; - Qualitative researcher adopts subjective stance; - Analysis of data is more difficult than quantitative data, requires filtering and arrangement; - Qualitative researchers develop the majority of their concepts during data collection and they re-examine and assess the data and concepts concurrently and interactively; - Research is means to explore actors' interpretations; - Relationship between researcher and subject is close; - Researcher stance is as an insider; - Emergent relationship between theory and research; - Research strategy is unstructured; - Scope of findings is ideographic; - Image of social reality is processual and social constructed by actor; - Nature of data is rich and deep.
- Both types of research methods use two processes: conceptualisation and operationalization; - Both approaches relate to the uniform principle of trying to explore, explain and predict social behaviour.	

3.2 Research Design

The scope of this project is limited to climatically similar locations as Kuwait. Thus, the engineering designs presented in this project are applicable within this climatic scope, i.e. hot climate, varying humidity at different times of the year, high winds speeds throughout the year, with extreme hot temperatures during the summer season.

As mentioned in the preceding section, the nature of the problem tackled in this project dictates using quantitative methods to understand and analyse the problem. In addition to the factors around understanding single sided ventilation in classrooms in Kuwait, several other important practical factors had to be considered when selecting the research methods for this project. These include: 1) Scope of the research; 2) Time and cost required; and 3) Accessibility of facilities. Within these constraints and the project objectives defined in section 1.3, the research methodology is now described followed by the field data collection details.

3.3 Modelling and simulation methods

The primary technical objective in this project is to investigate a single-sided ventilated room, and the performance of the proposed wind-induced natural ventilation strategy in terms of detailed airflow field. Three subcategories available for the modelling method are as follows analogue models, numerical models and physical model. In comparison to full-scale physical methods, analogue and numerical modelling techniques are cost effective and consume less time to evaluate the influence of different scenarios and parameters on natural ventilation. Furthermore, when conducting studies that required detailed air flow analysis, mapping the results from a small-scale model to the actual building may not be possible. For example, for a tall building, the wind profile on an external wall in natural conditions will be difficult to generate for a small-scale model. Thus, the results from a scaled down version of the actual building may not be applicable to the actual problem. In short, the boundary conditions are difficult to generate for scaled down models of buildings. Therefore, modelling and computer simulation are a useful method for the study of natural ventilation in and around buildings.

For analogue models, an analogue has to be created among the characteristics of two variables in order to execute these techniques. An explicit mathematical model for the ventilation processes, or a direct correspondence between the two sets of variables may be able to establish these analogies. The association between actual phenomena and analogue however is not perfect most of the time. The accuracy of the methods is dependent on the precision of the simulation and how perfect the information of different heat flow paths is (Hitchin and Wilson, 1967). However, studies of wind-dominated natural ventilation do not usually employ analogue models. Throughout the last decade, stack-driven ventilation is favourable in the available literature for the employment of analogue models. For reproducing the characteristics of stack-driven ventilation, analogue model is the better and easy option in comparison to other methods (Hunt and Kaye, 2006, Lin and Lin, 2014, Lin and Tsai, 2013). This is because the alternative can become too complex when there is a mix of stack and wind driven air flow, as is often the case in real weather conditions.

Certain problems are solved with the help of numerical approximation used in the numerical methods. Mathematical problems are formulated here and solved with the help of arithmetic operations. This method can be used for various fields of study; thus, it being utilized in the buildings for natural ventilation. The method can be based on very complex computer simulation models such as i) multi-zone network models, ii) zonal models and iii) computational fluid dynamics (CFD), on the other hand, a simple algorithm such as analytical and empirical models may also be used.

Considering the requirements and objectives highlighted at the start of Section 3.2, it is preferable to use simulation because it has the capability which enables various alternative parameters and designs to be investigated in a detailed manner, with relatively lesser time and cost involved. Moreover, there has been successful use of models for analysis of natural ventilation, driven by both stack and wind force, in context of detailed airflow distribution and indoor room temperature for a cross-ventilated and single-sided room as can be observed in the preceding section. Thus, in this study, the software tool DesignBuilder has been employed as the tool that performs the energy simulations for the defined scenarios. The following section presents further detail regarding this buildings energy simulation tool (DESIGNBUILDER SOFTWARE LIMITED, 2020).

3.3.1 DesignBuilder

The DesignBuilder software has been implemented at the tool in this study, to predict the thermal comfort, energy use and indoor air quality in the classroom. Additionally, its CFD capability has been utilized to understand the air flow velocity profiles in a greater depth. The CFD capability of DesignBuilder is similar to that of IESVE, however its CFD modelling capability is not comparable to standard tools for this purpose such as ANSYS or OPEN-FOAM. However, Design Builder fulfils the objectives of the work as the focus is not at a zone/sub-zone level, it is rather at a facility level.

DesignBuilder is a graphical interface for the energy simulation engine EnergyPlus (EnergyPlus, 2012). The interface allows easier modelling of the building geometry through a user-friendly graphical interface instead of coding in a text file as is the case in EnergyPlus. Access to a mereological database allows using weather data from different places around the world. Using the EnergyPlus simulation engine, the cooling loads can be model to account for the dynamic variations due to monthly or diurnal environment variations. Additionally, DesignBuilder has a built-in library of various HVAC modules that makes the modelling of the evaporator reliable and expedient. As it is based on the well-established EnergyPlus simulation engine for buildings thermal modelling, DesignBuilder is considered suitable for this project.

Finally, the computer simulation results are analysed to derive generalized conclusions within the scope of this project. As the computer model is validated against filed collected data, the analysis derived from the quantitative results from DesignBuilder can be consider reliable and objective. While Chapters 4 and 5 present the modelling, validation and results of the natural ventilation design and the classroom model respectively, Chapter 6 is the final part of the research design that allows the researcher to derive generalized conclusions in the final chapter of this thesis that is the contribution to knowledge generated through implementation of this quantitative research methodology.

3.3.2 Thermal comfort indicator selection:

As it will be seen in Chapter 4, the scenarios have A/C cooling only and natural ventilation-based situations. AC only cooling and natural ventilation leads to distinct indoor conditions that affect the choice of the thermal comfort metric. The measurement of thermal comfort in the baseline, A/C cooling only scenario can be considered steady state, for which Fanger's PMV is best suited. This is in line with the static PMV ASHRAE model (Dear, 2001). However, when natural ventilation is introduced, a feedback between the changing surroundings and the human body exists, for which adaptive comfort models are better suited (S Carlucci *et al.*, 2018) – hence the AHRAE 55 2017 Adaptive thermal comfort model is used for the scenarios where the wind-catcher natural ventilation exists (scenarios 2 – 4).

3.4 Data collection

In order to model the building and then to validate the model, several data are required. For modelling, the building characteristics, operational profiles, occupancy profiles, and weather data is needed. For validation, the energy use and indoor temperature is required.

A typical school was visited by the researcher on the 01-Jun-2017 to have a field data collection for the main research topic. The school location was in Ahmadi province in Fahad-Alahmad Area. The collection of data started by choosing a typical classroom with single-sided ventilation. This classroom was chosen under the school manager guidance for easier access. The measurements of classroom were 6 meters in length ,5.5 meters in width and 3 meters height with two wall windows size 1.5 meters width and 1.5 meters length with a total area of 2.25m^2. Also, to be mentioned that windows were partially opened with 20% at certain times and that was observed during the day visit. Figure 3-1 illustrates the outside single sided ventilated wall of the classroom.

Figure 3-1 - The classroom single sided windows

Also, the occupancy of the classroom as a daily average was of 29 student and the teacher. The furniture consists of wood and aluminium tables and chairs as shown in Figure 3-2. This information, along with the building characteristics and geometry were necessary for the computer modelling and simulation part of the research.

Figure 3-2 - The classroom furniture.

For recording air temperatures at 30-minute intervals for one-month period; the time interval was chosen to get the much possible accurate temperature changes in the hottest period of the year with reasonable resolution. However, it should be noted that the instrument has its own limitations e.g. the capacity for storing the measured data (memory) and the limited battery lift. These limitations led to some missing data during the field measurements. The average data for each hour of the day obtained from the period of measurements were therefore used for comparing with the simulated data. Figure 3-3 shows the location of the 8 HOBO logs used to collect the temperature data during the starting from 04-06-2017 to 04-07-2017. It was considered to get the most accurate temperature data by covering all possible area in the classroom including corners, centre and sides.

Figure 3-3 - The distribution of Temperature logs in the classroom.

In this study, an anemometer was used to measure and record internal air velocities. Figure 3-4 below shows the speed of air when the anemometer was placed near the air conditioning system (v = 0.9$^{m}/_{s}$) and when it was placed far away from the a/c system (v = 0$^{m}/_{s}$)

Figure 3-4 - Classroom internal Wind Speeds.

For lighting, the classroom had 2 typical 1.5 metres fluorescent lighting tubes with 58 Watts as shown in Figure 3-5 below:

Figure 3-5 - Fluorescent lighting used in classroom.

To simulate the classroom, it was necessary to know materials the classroom was built from and the geometry. In this case, the Ministry of Education, Department of School Building Maintenance for Kuwait was visited, to collect information on the classroom constructions. It was found that the classroom walls were built from Autoclaved Aerated Concrete, commercially known by ACC white blocks. Additionally, the walls had layers of plaster on the inside and the outside. The roof consisted of 4 layers plaster, concrete and bitumen sealant, and tile to the outside. The other important considerations include the location and orientation of the classroom and the positioning of its windows. These aspects are particularly important inputs for building modelling software. Also, the appropriate weather data need to be applied with the effects of sunrays on the classroom. This is illustrated in Figure 3-6; the test classroom is located 29° 7 58 N, 48° 6 42 E, at a magnitude of 34° NE.

Figure 3-6 - The Compass used to determine the window facing location (iPhone compass app).

The classroom uses an electric split system air conditioning system illustrated in Figure 3-7. The specifications of the air conditioning system were recorded for the modelling purposes. The expenses to put up a weather station outside the tested classroom were not available for this project, therefore the average external wind speeds at different times of the day in the month of June used in this study were retrieved from the Meteorological Department of Kuwait. The data on wind speeds collected from the meteorological department was used in every simulation conducted in this study.

Figure 3-7 - Split ac unit in classroom.

Temperature loggers recorded all temperature reading in each location for one month started from 04-06-2017 to 04-07-2017. A program called HOBOware was used to control theses logs by choosing the starting of the period. Once the period finished the data was exported to a Microsoft Excel file to see the temperature changing during the specific dates on each location of the classroom. As an example, Figure 3-8 shows temperature reading in centre of the classroom at a height of 80 cm from the ground the student’s desk height. The average temperate goes to 28.18 ℃ according to the readings.

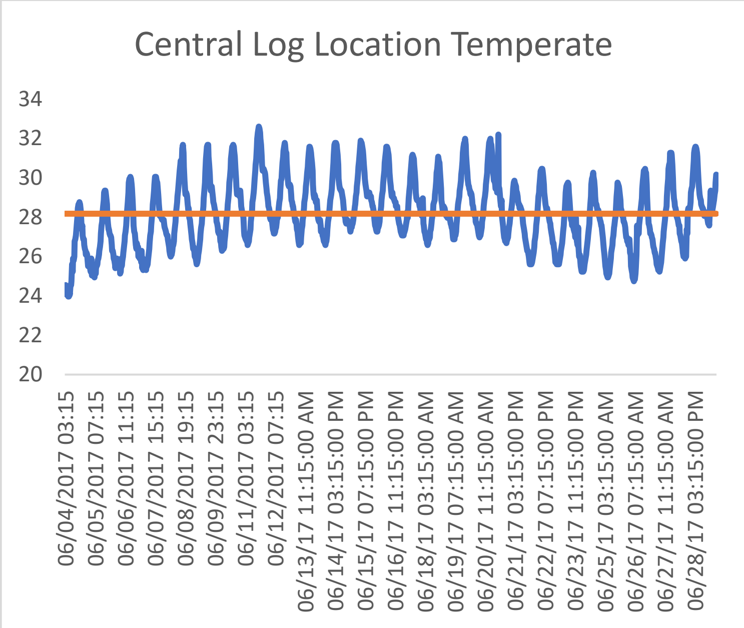


Figure 3-8 - Temperature readings of the central location in the classroom.

Also Figure 3-9 shows temperature reading of the location near the A/C split unit used with a height of 1.5 m from the ground that the average temperature goes to 28.38 ℃ as the set point of the A/C was 20 ℃ . It's been noticed that the temperature was going up and down starting from 20 ℃ to 37 ℃ due to the opening and closing of the door and the activities done near that location by the teacher using projector and learning tools.

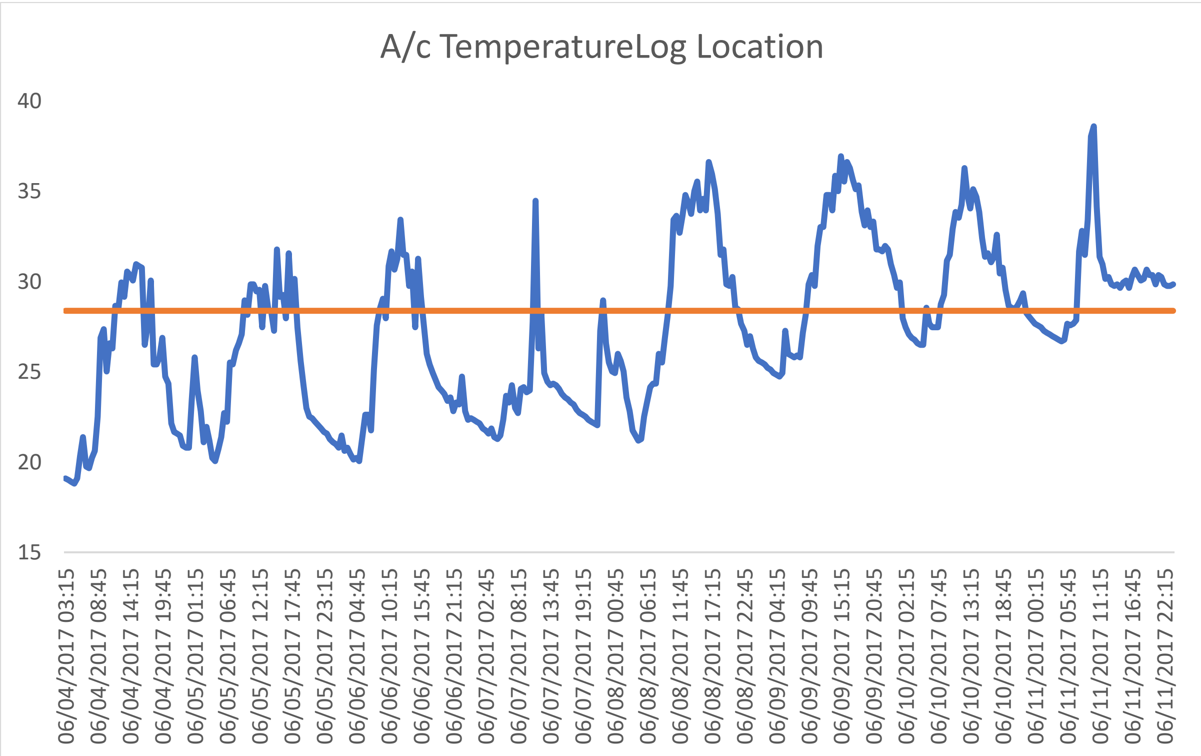


Figure 3-9 - Temperature Reading on the location near the A/C unit – over one week in June.

For third important location was the windows near location which is been used sometime to have fresh air entering the classroom as the operating hours of a/c all day lead to unhealthy environment inside the classroom. The log was setup between the two openings windows. Figure 3-10 illustrate the temperature recorder varying between 25 ℃ and 45 ℃ which means sometimes windows are fully opened therefore the logs recorded the wind air temperature entering the classroom. The average temperature was 33.9 ℃ which is can be consider as normal because of the openings windows during freshening the air inside the classroom.

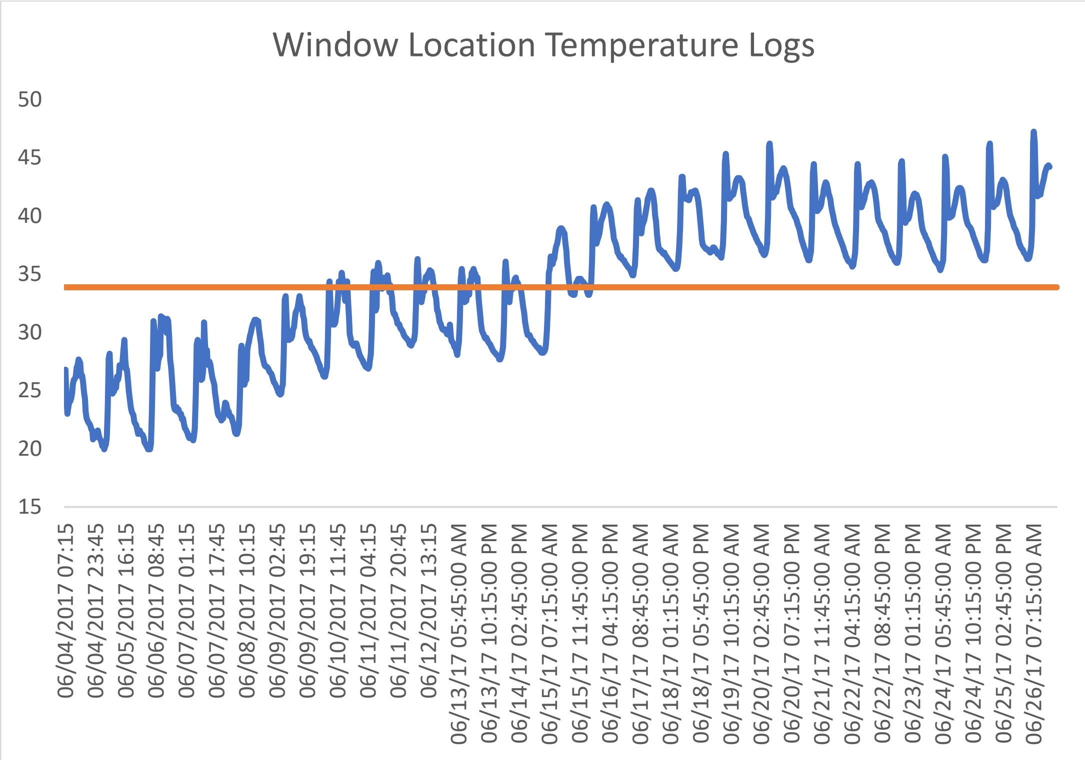


Figure 3-10 - Temperature readings on the Windows operation.

In addition to the data required for creating the classroom model, the energy use data was collecting for model validation. In general, governmental schools don't pay any cost for electricity or water usage so the meter readings are not important for the building operator. The researcher collected data from the school electricity meter which was installed about nine years ago and on 31-05-2018, the meter reading was 11051600 kWh. Using national scale statistics (MEW, 2014), it can be estimated that 60% of the electrical energy was used for building cooling. This equates to 6,630,960 kWh for this school's case. Therefore, on average, the school uses 736,773 kWh yearly on-air conditioning systems. The school consisted of 24 classroom, 4 teaching department offices and the main principle office with facilities. The school area was approximately $2500m^2$. Due to confidential rules the school plans as not available to share by the Ministry of Education or Ministry of Construction.

Chapter 4 – Modelling and validation

4.1 Introduction

In this chapter, the structure of the investigation and the scenarios to be compared are defined. Furthermore, a description of the model development within each scenario is provided. The objective of this modelling exercise is to **'investigate whether the wind catcher system has the potential to enhance airflow and provide adequate cooling inside a single-sided ventilated classroom and consequently enhance human thermal comfort.'** In the process of addressing the above objective, the energy requirements and indoor air quality was also assessed, as these are important aspect of indoor spaces and are interlinked with HVAC systems that ensure thermal comfort.

To develop a reliable model, a validation exercise is conducted by comparing the predicted thermal parameters against measured data obtained from the in-site measurements for the school building. Additionally, an analysis of the software tool's calculation method, turbulence models as well as its capability for thermal parameters predictions under particular building configurations and specific weather conditions is also investigated. The software's default weather data and the user's ability to generate a simulated model and to define other related settings were also examined – using a comparison between the software's default weather data for Kuwait and the average weather data obtained from Kuwait Meteorological Department.

4.2 Study design

The proposed ventilation-based technology in this work is the wind catcher system which is to be examined and tested under the local weather conditions. The performance of this system is to be measured in terms of thermal comfort and energy requirements. To assess the thermal comfort of occupants, it has been established in the previous chapters that the percentage hours of comfort/discomfort based on the PMV indicator is considered as a suitable indicator to assess the impact of the proposed ventilation strategy. Moreover, additional significant parameters used to investigate the effectiveness of the proposed wind catcher strategy include the room's temperature and indoor air speeds obtained from the classroom simulation using Design-Builder with the EnergyPlus simulation engine. The analysis is structured by comparing the following scenarios

1. Base case – A/C based cooling only
2. Scenario two: Wind-catcher based natural ventilation only

3. Scenario three: Wind-catcher with evaporative cooling included
4. Scenario four: Wind-catcher with evaporative cooling plus A/C for backup

In above scenarios, the baseline captures the real-world typical conditions currently found in Kuwaiti classrooms. Scenario 2 replaces the A/C with the wind-catcher, but as it is not expected to fulfil the thermal comfort requirements in the extreme hot climate of Kuwait, Scenario 3 includes evaporative cooling as well. Finally, Scenario 4 adds a backup A/C system in case the natural ventilation-based design in inadequate. Modelling of each scenario along with validation of the base case if provided as follows.

4.3 Building characteristics

The based case simply required the creation of the classroom model serviced by the A/C system as used at present, for the location in question, using Kuwait's weather data as an input to the model. To mirror the actual situation, the classroom door was set "open" due to the real-life scenario as the school rules consists of door being open all the time, and so was the external opening to realize a single-sided ventilation room. The default wind coefficient values in the DesignBuilder were used since these values are recommended for buildings with less than three storeys.

Before proceeding with the modelling process, the input weather file (.epw) was validated against Kuwait' MET data. First, DesignBuilder's default weather data for Kuwait based on the ASHRAE Weather for Energy Calculation IWEC was compared with the Meteorological Department of Kuwait's data for the location. It was established that the software's default relative humidity and dry-bulb temperatures closely matched the data obtained from MET with the two data sets having average relative errors of 1.7% and 1.6% respectively. These percentage of errors are sensible and therefore the Kuwait weather data available in the DesignBuilder database is considered appropriate for this study. For the base case model development, building constructions and operation/occupancy schedules, location and geometry data are provided next.

4.3.1 Building construction

The modelling of a building requires the knowledge of building constructions such as the floor, walls and roof material and thickness, glazing covered area and internal partitions. This information along with furniture (that may increase the thermal mass of the indoor space), lighting and HVAC overview is provided in the following table. Most important in this list are the external walls and floor, roof material and glazing, as these have the most effect on the results of the simulation work.

Table 4-1: List of the Classroom materials and modelling settings - (Source: Department of maintenance ministry of education field visit 2017).

Elements	Details
External wall materials	Limestone tile (50.00mm thickness) attached to an ACC BLOCK (200.00mm thickness)
Internal walls materials	Brick ACC Block (200.00mm, U-Value 0.5678) with plaster on both sides
Floor materials	Concrete covered with ceramic tiles
Building roof	Concrete with (200.00mm thickness with 20% steel 20, 18, 16 mm thickness)
Ceiling material	Gypsum Board (15 mm thickness) no insulation
External glazing	single glazed 6mm with 30% glazed
Windows	2 × Windows (2.25 m^2)
Occupancy	29 (average)
Lightning	Fluorescent lights 58 Watts
Furniture	Studying tables and chairs, (teaching board, projector when needed)
HVAC systems	A/C split system with 18000 BTU (5.27528 KW)

The building walls material consist 4 layers the outside layer was yellow colour limestone with a thickness of 50.00 mm going in depth a plaster layer of 20.00 mm was attached to the wall brick (AAC Block with 200.00 mm thickness) finally the inner layer was 13.00 mm single layer of plaster.

The school building Roof material consist also from 4 layers the upper outside layer was ceiling tiles with a thickness of 25.00 mm going in depth Bitumen layer of 20.00 mm was attached to the concrete slab (200.00mm) to isolate any leakage from rain water etc, and the inner final layer was 13.00 mm plasterboards.

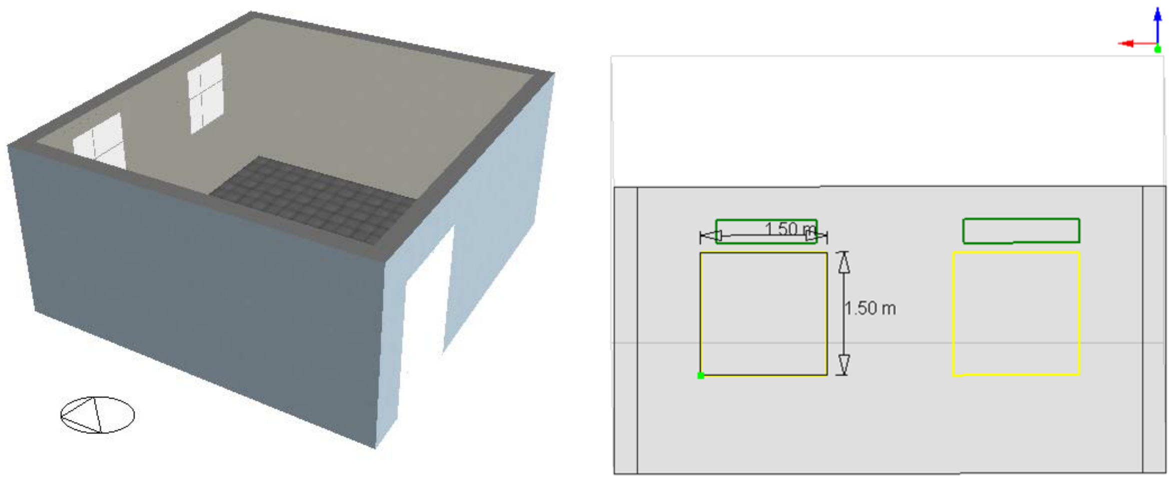


Figure 4-1: Left: 3D axonometric view for the classroom showing the windows and door openings. Right: plan view showing the dimensions of the windows

The classroom glazing consisted of two windows size 1.5 meters width and 1.5 meters length with a total area of $2.25m^2$, and one entrance door (see Figure 4-1 for axonometric and plan view of the classroom). The windows were built from aluminium frame with single glazed glass. The windows glass was clear 6mm thickness with 30% glazed. All this information was very important in creating the design builder case to simulate the exact and best thermal predicted results. The building roof consisted of reinforced cement concrete which is mixture of Portland cement, stone and fine sand. Additionally, steel is placed in concrete to make it more resistant to compression and bending.

4.3.2 Classroom Cooling

As mentioned earlier in the literature review, no heating is required, and Kuwait normally depends on AC systems for cooling. In this case, the classroom had an 18000 BTU (5.28 KW) AC split unit supplying the cooling effect for the occupants with recirculated air. The A/C was operated manually by the teachers based on the audience comfort resulting in high levels of thermal comfort. The A/C operating schedule was created in the model based on the teacher's actions for the daily usage – as it reflects the actual use in the baseline scenario.

4.3.3 Ventilation

The ventilation modelling is done based on infiltration, windows opening/closing, and mechanical ventilation corresponding to the scenarios defined. For the baseline, the ventilation occurred due to infiltration air flow through the building envelope in the AC mode cooling scenario, as well as opening windows whilst the AC is operating which is representative of the actual situation. The infiltration was driven by wind and the window opening – as this corresponded to the actual situation as observed in the field visit and physical inspection of the classroom. For the modelling of the wind-catcher, openings within the design allow developing the air flow. The design is depicted in the figure below.

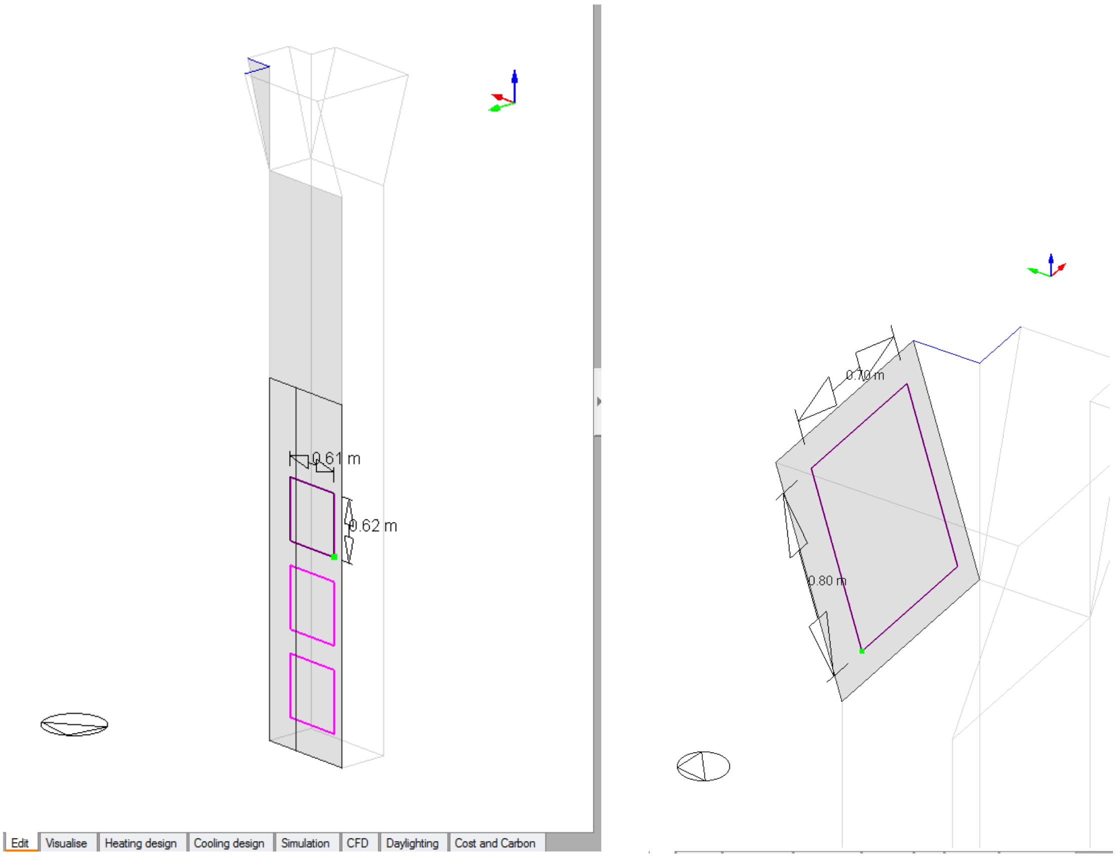


Figure 4-2: Left: Wind catcher openings dimensions, Right: Wind catcher head, opening dimensions

4.3.4 Lighting and occupancy schedule

The lightings consisted of typical Fluorescent lights. According to the Ministry of Education (school building and maintenance department) rules and regulations, an On/Off schedule was created to express the real daily usage and help to calculate the best accurate energy usages. Aligning with the school opening hours (building occupancy during 7am to 3pm, with pupils from 7am to 1pm), the schedules were created. At 7am until 9am the lightning was partially on (50%); from 9am to 3pm it was fully on, while after that it would be switch off as the school day ended. This schedule is summarized in the table below.

Table 4-2: CLassroom Lighting Schedule.

	07:00 AM	9:00 AM	11:00 AM	12:00 AM	13:00 AM	15:00 PM	24:00 PM
Weekdays	on/off	on	on	on	on	off	off
Weekend	off	off	off	off	off	off	off
Holiday	off	off	off	off	off	off	off

4.3.5 Location and Geometry

The location and simulation setup are summarized in Table 4-3. The weather file for Kuwait international airport (provided by KIST) was used with its corresponding lattitude and longitude. This location is near the school site as the majority of Kuwait residential area is located near the coast and the airport is in the middle. The elevation was at 55m while the buiding was oriented 36 degrees to the north. The total simulation hours were 4392, which corresponds to six months, which in this case covered all the summer months from April to September (included). The period of test examined is all the year but a focus on the summer period was chosen as the collected data and field trips were in the summer period. Also, as this is hottest period in the year which needs the most cooling system, it was sensible to focus on these six months.

Table 4-3: Specification Inputs used in Designbuilder.

	Value
Program Version and Build	Energy Plus, Version 8.5.0- c87e61b44b, YMD = 2018.11.07 14:07
Run Period	SCHOOL IN KUWAIT (01-04:30-09)
Weather File	Kuwait Intl Airport - KWT KISR WMO#=405820
Latitude [deg]	29.22
Longitude [deg]	47.98
Elevation [m]	55
Time Zone	3
North Axis Angle [deg]	36
Hours Simulated [hrs]	4392

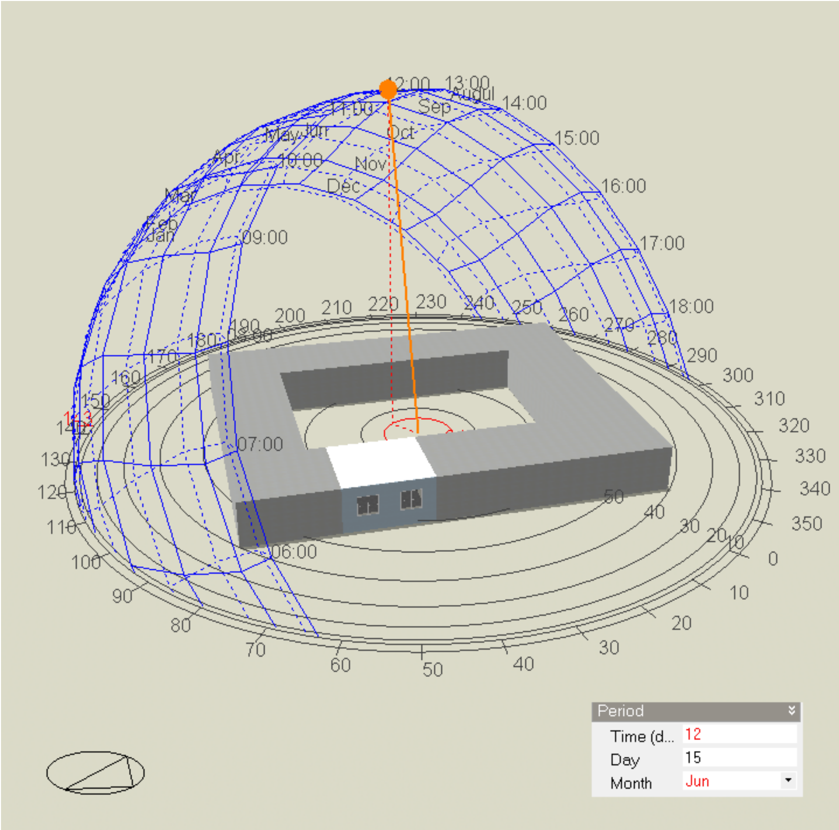


Figure 4-3: School building orientation with the sun path timing – with the classroom shown in white colour.

Figure 4-3 depicts the perspective view of the whole school building modelled showing the orientation with the sun path. In addition to the weather and building orientation, a material project profile was created for the case study that described the wall materials and layers. The second profile for the lighting used in the classroom were typical florescent lights while the HVAC profile which chosen with 18000 BTU/h A/C split unit which equals to 5.2kW. Last but not the least, the building occupancy profile is another important input that effects CO2 levels, internal gains and other parameters. This was selected as 29 people in the classroom to reflect reality.

4.4 Scenario 1: Base Case – air cooling only

the base case represents the actual scenario observed during field visits. In this case, the classroom indoor space is conditioned using Air conditioning only, in combination with manually opening of windows when the cooling is insufficient. As the climate is predominantly hot through the year, there is no heating during the winter. The validation of the baseline model based on field collected data is presented next.

4.4.1 Base case validation

First an assessment of the DesignBuilder weather was done. This was needed to make sure that the source file in design builder is in agreement with the MET department weather station data, particularly the temperature and wind speed. For this purpose, a comparison between the two sets of data was done as follows.

DesignBuilder uses EnergyPlus format (epw) hourly weather data for defining external conditions for all simulations. These data sets are derived from hourly observations at a specific location over past many years. For Kuwait, the weather information is obtained from KISR (Kuwait Institute of Scientific research)(KISR, 2019).

Table 4-4: Outdoor Monthly maximum daily obtained from daily averages – retrieved from the Kuwait Meteorological Department (MET) and Designbuilder EnergyPlus (DESIGNBUILDER SOFTWARE LIMITED, 2020)

Month	**Measured Data (Average)**	**Design Builder Default Data**	**Relative Error**
	(MET, 2018 C)	(Design Buidling ref), C	%
Nov-17	28.89	30.5	-5.28
Dec-17	23.86	23.5	1.53
Jan-18	22.17	23.5	-5.66
Feb-18	25.34	26.5	-4.38
Mar-18	31.71	31.8	-0.28
Apr-18	32.65	34.0	-3.97
May-18	39.43	41.2	-4.30
Jun-18	45.66	47.9	-4.68
Jul-18	47.72	46.9	1.75
Aug-18	47.00	49.7	-5.43
Sep-18	45.60	46.6	-2.15
Oct-18	36.81	39.0	-5.62

As evident from the above table, the error between the weather file and the collected data is within 6%, which is acceptable. Table *4-4* shows the comparison of monthly weather maximum monthly air temperatures obtained from MET and Energy Plus. The plot depicts a good agreement between the two data sets for average air temperatures. The relative errors between the data sets were recorded between -5.96% and 1.7%, resulting in a room mean squared RMS error of 4.37%.

In addition to the average wind speed, the maximum air speed over the year has also been compared. Again, there is good agreement in trends between the DesignBuilder/Energy+ profile and the one collected from MET, Kuwait. The relative error ranges between 5%, but with most months, espcially the summer months wihtin 2.2%.

Table 4-5: Outdoor Wind Data obtained from the Kuwait Meteorological Department (MET) and Designbuilder EnergyPlus weather data for Kuwait

Month	Measured data (Average data) (MET, 2018) (m/s)	DesignBuilder's default data (DesignBuilder, 2006b) (m/s)	Relative Error (%)
Nov-17	10.0	11	8.9
Dec-17	10.1	11	8.2
Jan-18	10.9	10	-9.2
Feb-18	12.0	12	-0.3
Mar-18	11.8	12	1.5
Apr-18	13.1	13	-0.7
May-18	11.7	12	2.3
Jun-18	14.9	14	-6.7
Jul-18	14.5	14	-3.8
Aug-18	13.2	13	-1.6
Sep-18	9.8	9	-9.0
Oct-18	9.9	11	1.5

This table emphasizes a good agreement between the two data sets for average air temperatures. The average relative error recorded here was only -0.75% and in most cases the absolute differences is less than 0.98 *m/s*. Hence, these are acceptable results. This is also due to the fact that both EnergyPlus and the MET data are based on the weather station in Kuwait City. This difference may have an effect on the simulation results of indoor air velocity as the software may give an over-predicted result for the case as it's located in area Fahad Al Ahmad. However, it should be noted that this default wind speed data will be adapted in the main study in order to investigate the effectiveness of the proposed strategy for inducing indoor air movement and to examine the effect of various parameters on its performance.

The base case (which is the school classroom without any improvements) was simulated for a year. The simulated room air temperature is illustrated in Figure 4-4. The analysis day was chosen to be 15th of June to match the day of starting measurements (Data collection from the field). The plot shows that the variation in indoor temperature and the as retrieved form the HOBO data logs. The average classroom temperature as simulated using DesignBuilder is 27.75 for this day. As the actual indoor air temperatures ranged between 28.2 ℃ and 29.5 ℃ indicating a difference of (1.3 ºC), this is an error of 4.68% between the predicted and measured values. This percentage error is tolerable, and the software is therefore capable of predicting internal air temperatures for a given external thermal surrounding.

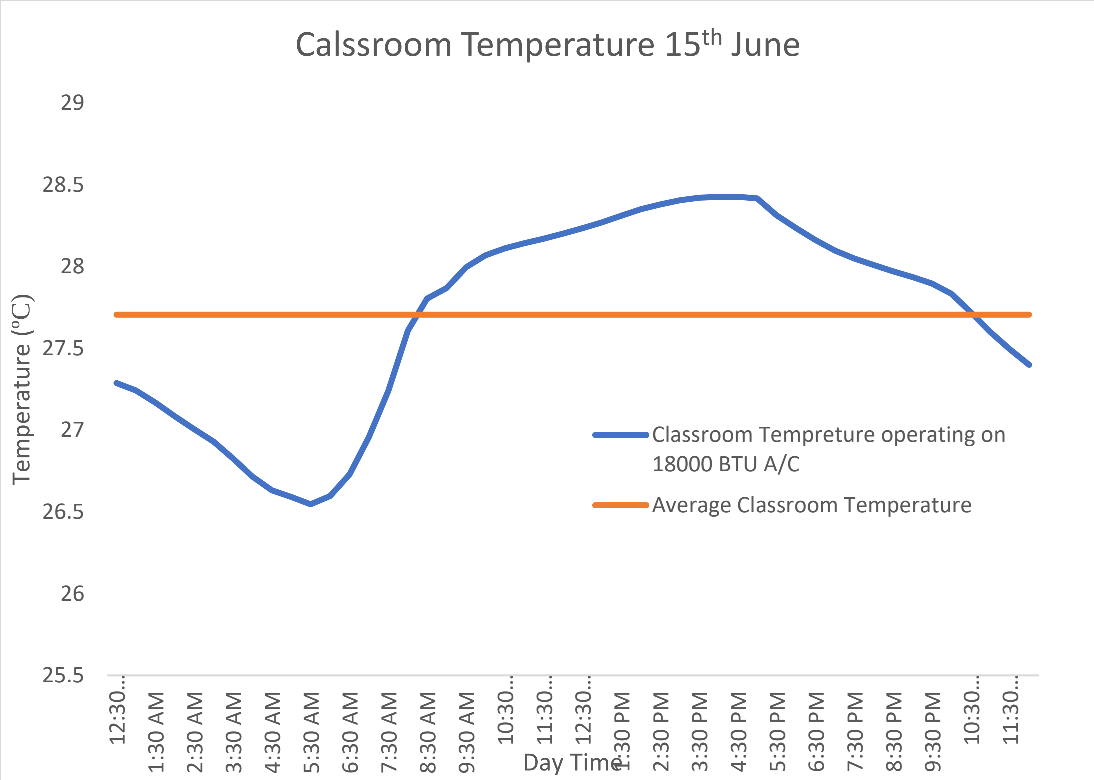


Figure 4-4: Classroom Temperature on 15th June calculated using Design Builder with A/C split unit 18000BTU.

In summary, a number of parameters were used for the validation of the model. This was important as the validity of the different variant scenarios directly depends on the validity of the base case model created in the software. Table 4-6 provide this summary.

Table 4-6 – Validation exercise of the base case scenario

Parameter	Maximum Relative error	Maximum Absolute error
Outdoor peak daily temperature	6%	2.32 °C
Average monthly peak temperature	3.8%	1.7 °C
Average monthly wind speed	4.68%	1.32 m/s
Monthly average wind speed	9.03%	0.78 m/s
Monthly maximum wind speed	5%	0.55 m/s
Peak summer indoor air temperature	4.86%	1.32 °C

This table shows that while some of the percentage make look large, the absolute amount of maximum error observed between the simulated as measured data is very small, and therefore acceptable for our analysis. However, the results generated are subject to this error, which should be kept in view when interpreting the results. It should be noted that for a peak summer day (15th of June), the temperature is around 27.8 ℃ which is clearly too high to ensure good thermal comfort. This means that the currently available A/C setup is not able to deliver the required thermal comfort (which should be less than 10% PPD according to the ASHREA 55 standard). To address this issue in an energy efficient manner, the following scenario introduce designs solve this problem.

4.5 Scenario two: Wind-catcher based natural ventilation only

As this project proposes an integrated wind-catcher system, its model description is now provided. It includes a wind-catcher supply terminal and an air extract that uses natural draught, the wind catcher system is simulated with clay conduits mounted inside the device to enhance heat and mass transfer. Based on the previous studies as detailed in Chapter 2, the wind-catcher needs to be at least 2m in height in addition to the roof. In the design for this work, the wind catcher in Figure 4-5 is a total of 3m above the roof (2m shaft and 1m head). It is rectangular in cross section and has four openings to allow the inflow of air from any direction. The wind-catcher head measures 1m x 1m with the vents dimensioned as 0.7m x 0.8m in area. Furthermore, bulk airflow modelling in DesignBuilder allows modelling and understanding of the macro patterns of air flow development due to natural ventilation – and is therefore used for the modelling in this scenario.

For this base case scenario, the proposed strategy's ability to enhance air movement in a classroom with single-sided ventilation and consequently enhance thermal indoor comfort was investigated. The classroom under study integrating the wind catcher was simulated in DesignBuilder's under the specific weather conditions for two periods (i) A summer period (April – September) and (ii) A winter period (October-March).

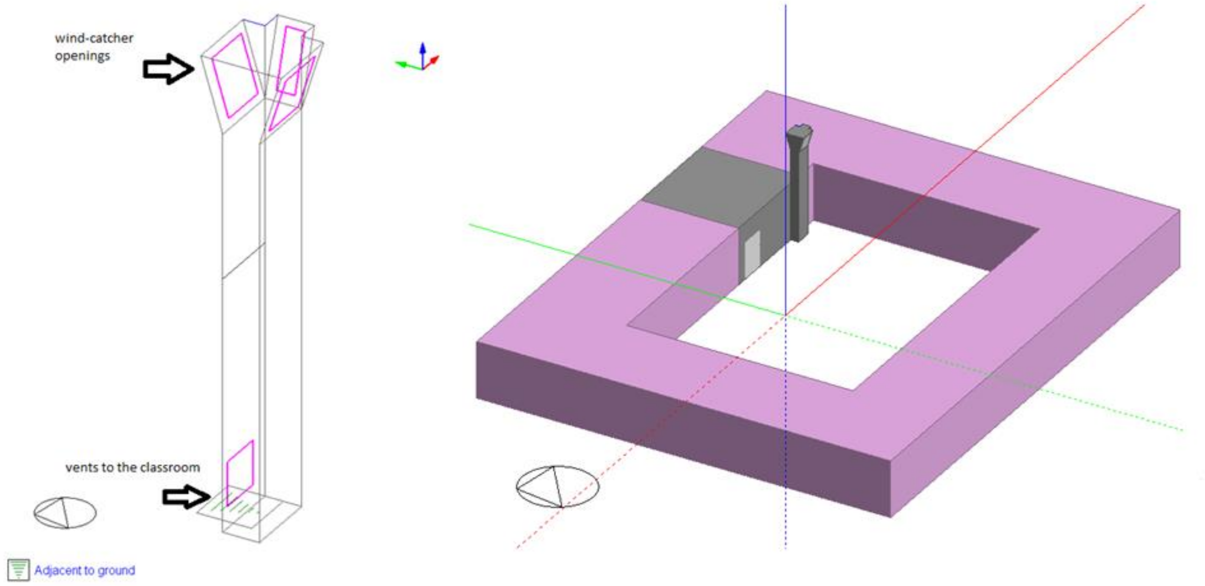


Figure 4-5: Modified Classroom with wind-catcher. The wind catcher is 1m × 1m in cross section, with four entry vents dimensioned as 0.7m × 0.8m. Four vents were chosen to allow inflow of air from any direction, to cater to changing wind directions. This design is based on the results of several studies detailed in Section 2.4.3 and Section 2.4.4 with its performance tested in DesignBuilder/EnergyPlus simulation (Chapter 5).

The classroom under study was integrated with the wind catcher device to examine the effect of the device in increasing air movement and consequently thermal indoor comfort. The DesignBuider modelling HVAC system mode was set to (Natural ventilation – No Heating/Cooling). The air entering the wind-catcher that passes to the classroom is modelled as a bulk air flow (means the air moving from high pressure space (outside) to a lower pressure space (classroom).

4.6 Scenario three: Wind-catcher with evaporative cooling included

Detailed HVAC system was used to model the evaporative cooling direct system by adding water pads to cool the air coming from the outside environment to the inside of the wind catcher, to pass it to the classroom. The figure below illustrates the wind-catcher is linked to the classroom through the vents and a convector unit with wetted clay walls and water spray for cooling air. Incoming air first passes through the convector unit and cooled before flowing to occupied indoor spaces.

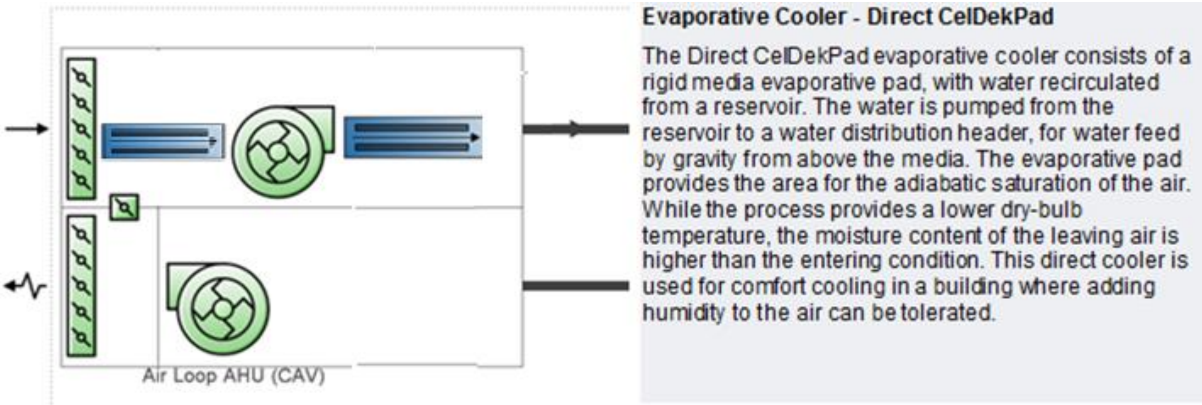


Figure 4-6: Model of the HVAC system for the Evaporative cooling for the wind-catcher using DesignBuilder(DESIGNBUILDER SOFTWARE LIMITED, 2020).

To model the evaporator, the pre-existing block in DesignBuilder HVAC shown in Figure 4-6 was utilised. From the figure above, a HVAC system is shown which consist of an evaporative direct cooling system (water air only). In Figure 4-7 the specifications of the evaporative pad are provided. This was chosen in the modelling of the evaporative cooling based on the size and outline of the wind-catcher integrated to the classroom, which has been examined from a personal engineering sense of the researcher. Therefore, air temperature entering the classroom will vary depending on the outside weather air temperature.

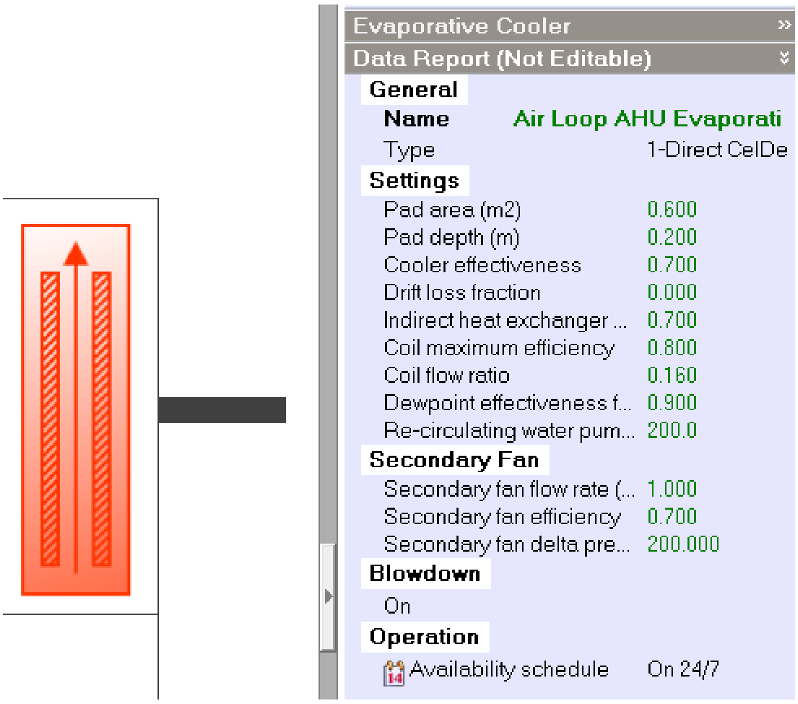


Figure 4-7: Evaporative cooling specifications used from the experimental work done (Design-builder).

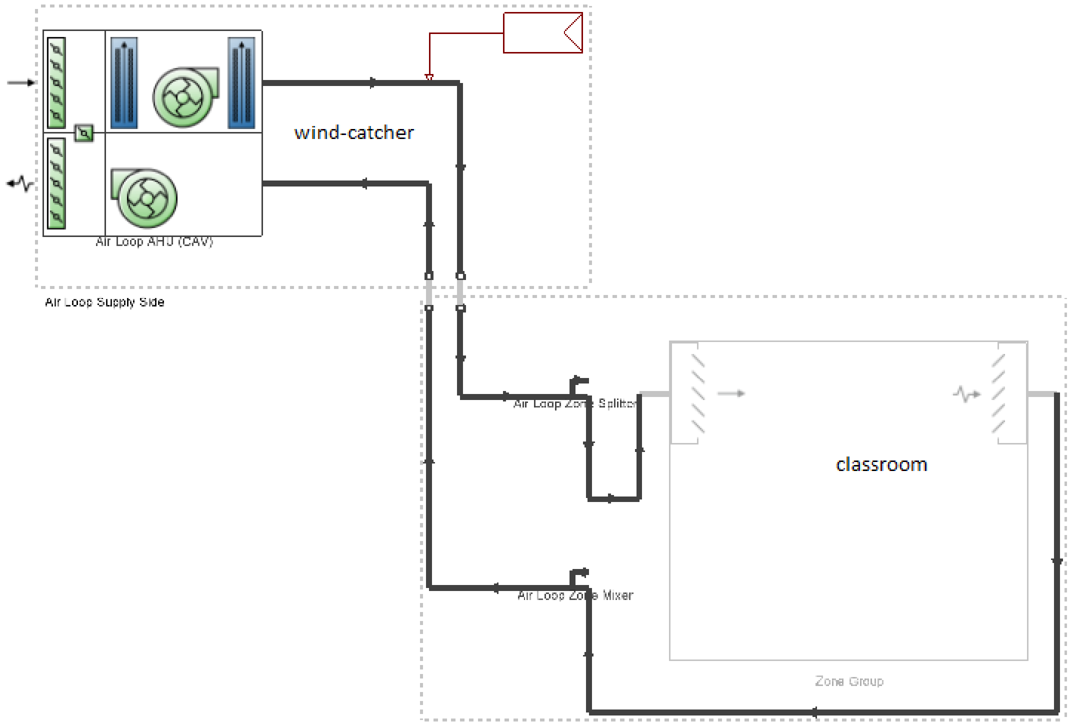


Figure 4-8: Evaporative cooling system attached to the classroom.

Figure 4-8 illustrates the HVAC detailed system modelled in Design-Builder to act as the evaporative cooling system. It consists of direct evaporative cooling with water pads. The fan in the system was chosen to be variable to work based on the outside wind speed, to have the effect of the wind catcher driving the air passing the HVAC system continuing to the classroom.

4.7 Scenario four: Wind-catcher with evaporative cooling plus A/C for backup

In this scenario, to add more cooling efficiency to improve the overall thermal comfort, both evaporative cooling and the A/C split unit have been modelled. The set point for the A/C system was chosen to be at 27.5 ºC – as this was the setpoint in the baseline scenario in practice. Therefore, if the classroom temperatures go up that value the A/C unit will start to operate and supply further cooling load to the surrounding space to achieve a good thermal comfort for the occupants.

The following chapter presents the results of the modelling of the afore mentioned scenarios in terms of

1. Thermal comfort
2. Indoor air quality
3. Energy requirements

In addition to the above, ventilation and airflow is also assessed for the most promising scenario to develop a deeper understanding into that scenario.

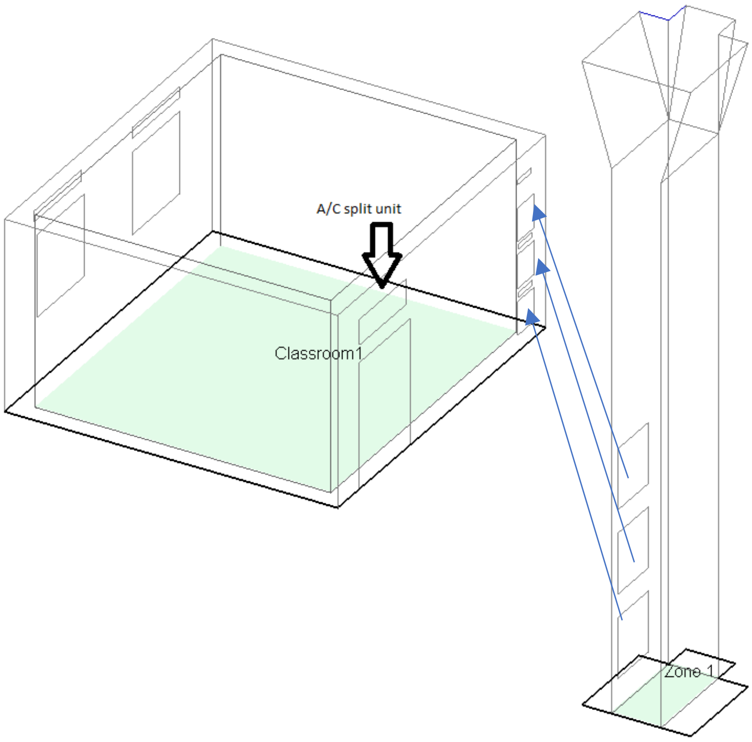


Figure 4-9: Classroom integrated with wind-catcher evaporative cooling + A/C split unit (Design-builder).

Chapter 5 – Results

In this chapter, for each of the scenarios defined and described in Chapter 4, the thermal comfort, indoor air quality, ventilation and airflow, and energy use results are provided. Among these parameters, more focus will be on thermal comfort and energy use, to fulfil primary aim of this project. These will be objectively analysed in Chapter 6 to develop a discussion around the advancement in knowledge that has been achieved through this work.

5.1 Scenario 1: Base case – A/C based cooling only

The baseline scenario is that of full HVAC air conditioning and has been selected to match the actual baseline conditions in the classroom. The indoor and outdoor temperature profile is provided in Figure 4-4 for the typical summer day of 15th June. The indoor classroom temperature matched closed with actual measurements form the HOBO data loggers, with a maximum difference of 1.32°C or 4.68% between measured a simulated data – considered acceptable for this study. It should be noted that the generated results are subject to this limitation of this accuracy tolerance, i.e. within 5%.

As the baseline scenario is an A/C cooled building, without any kind of natural ventilation intervention, the indoor conditions could be considered slowly changing (or steady state), thus making Fanger's PMV the most suitable thermal comfort indicator in this case. Figure 5-1 shows the PMV distribution for this scenario, as calculated by the model – for all year occupied hours. The histograms show that most of the people would be comfortable (-0.5 < PMV < 0.5), however a significant number are predicted to be at a value of 1 and -1 on the thermal sensation scale. The ASHRAE PMV model stipulates that human thermal comfort of less than 10% PPD corresponds to (-0.5 < PMV < 0.5). However, Figure 5-1 shows that a total of 1201 hours are predicted to be out of this range, which is 27.9% of the total votes. **Therefore over the year, 27.9% of the hours in the baseline scenario does not fullfill the ASHRAE PMV stipulation**, and it can be said that people are likely to not feel comfortable for this amount of time.

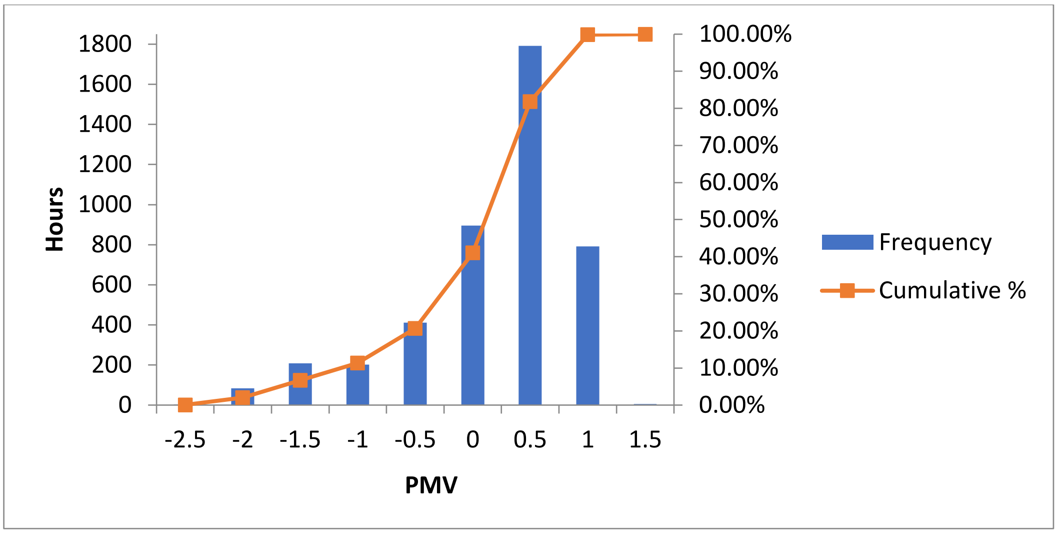


Figure 5-1: PMV Frequency for the classroom with A/C only

These results on average show that while most people are thermally satisfied, there are more people who are feeling too warm as compared to those feeling too cold. However, it should be noted that previous studies have shown that this may even be an under prediction. (Al-Rashidi, Loveday and Al-Mutawa, 2009) have shown through their case study of classrooms that the PMV indicator under predicts the warmness perception of school children in Kuwait. This means that in reality, people are likely to feel more unsatisfied due to overheating in the Kuwaiti classrooms. Nonetheless, this established a baseline of thermal comfort which we can use for comparison with the rest of the scenarios. Note that this is an avenue for future work, as the PMV indicator underpredicts the thermal comfort of classroom occupants in Kuwait.

Coming to the air quality consideration, the results for CO2 levels are presented in Figure 5-2 for typical day in summer. The horizontal black line shows the acceptable CO2 levels as stipulated by international standards. The result show high CO2 levels (2000-4500), due to lack of air change rates inside the classroom. According to ASHRAE, the recommended CO2 level in classrooms should be no more than 700 ppm above outdoor air. Since outdoor air is approximately 400 ppm, indoor CO2 levels should be no more than 1,100 ppm. Based on this information the result showed that the classroom CO2 concentration are **80% of the time outside the acceptable level**. It can be seen that as soon as the pupils arrive and the building becomes operational, the CO2 levels go well above the threshol of 1100ppm CO2, right until the later afternoon when the classes are finished. Clearly, in terms of air quality, this baseline scenario with A/C only may be somewhat suitable for thermal comfort, but it certainly is not performing well in terms of air quality.

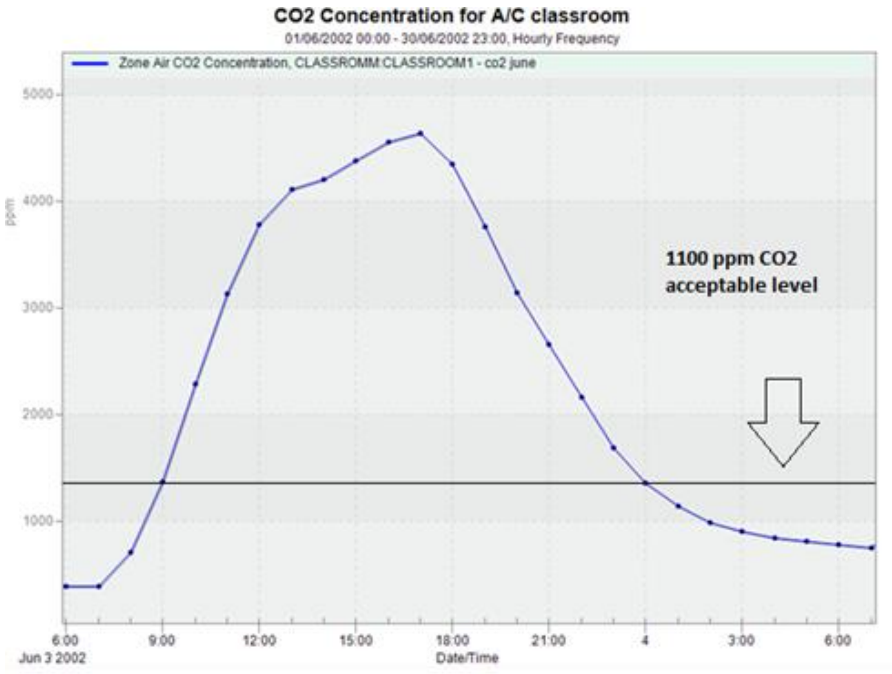


Figure 5-2: CO2 Concentration for A/C classroom.

The air change rate has been analysed and presented in Figure 5-3– analysing (left) a typical week June (right) all year. The air change during the occupied hours during the teaching days hovers between 0.8ach and 0.98ach. For the whole year, the average air change rate, derived from Figure 5-3 (right) – results in an average value of 0.85 ach (23.375 l/s) during the occupied hours.

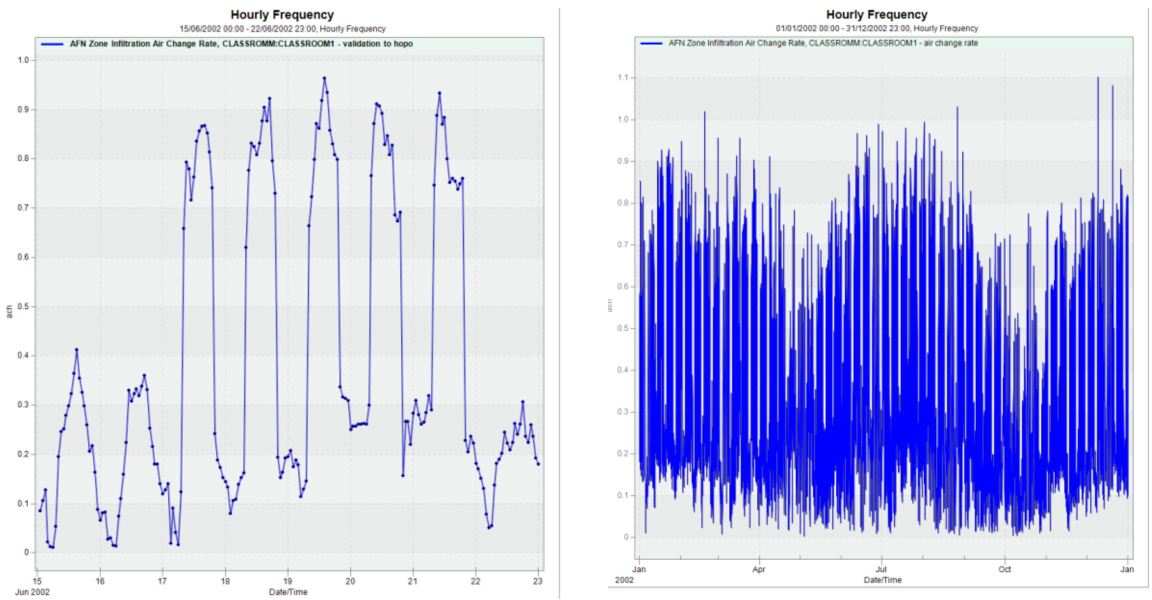


Figure 5-3: Air change rate inside the classroom due to infiltration. Left: Results from a typical week in June. Right: Yearly air change rage profile, leading to an average of 0.85 ach (23.375 l/s).

5.2 Scenario two: Wind-catcher based natural ventilation only

This scenario presents the results of the natural ventilation strategy using the wind-catcher system. To organize the results, summer and winter period results are presented separately. In both cases, typical representative weeks are chosen as 15th June - 22nd June for the summer, while 20th Jan - 25th of Jan for the winter, as they as they represent extreme conditions. This is chosen especially since in hot climates, in only natural ventilation designs without any aid of mechanical cooling, it is not expected to deliver fully thermally comfortable indoor conditions owing to the extreme summer and winter temperatures in Kuwait – represented with the winter and summer week periods chosen here, thus evaluating the performance of the design in the harshest of conditions through the year.

5.2.1 Summer period results

First, the indoor air temperatures and heat gains are simulation for this scenario. Figure 5-4 illustrates how the wind-catcher system works with ventilation only mode by simulation a week in the hottest summer month (15 June to 22 June). As the outdoor temperature varies between 26 °C and 47°C, the indoor temperature varies between 31 °C to 41°C during the day inside the wind-catcher-tower in the summer period. Considering that these results are for 100% natural ventilation mode, this significant reduction in air temperature in the wind-catcher is an indicator of the possible good performance of this design when combined with evaporative cooling.

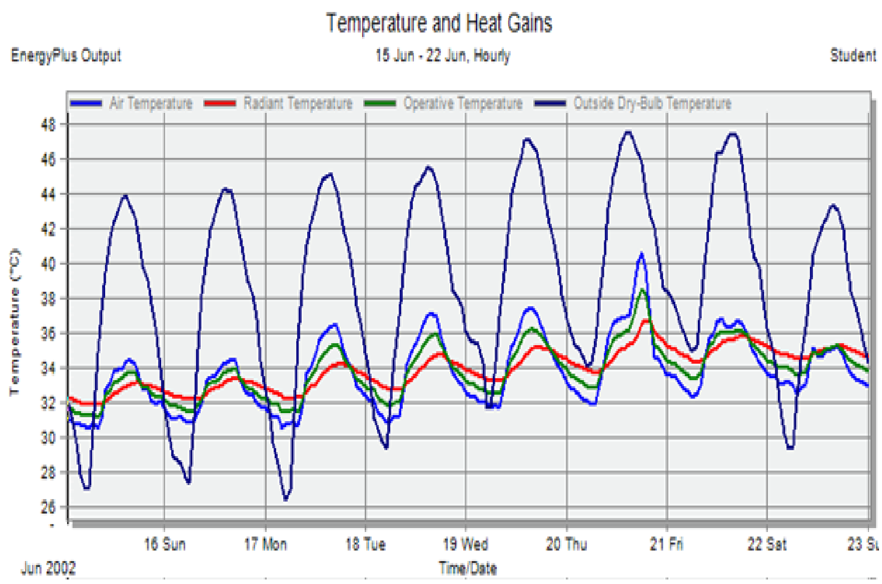


Figure 5-4: Conditions inside wind tower for natural ventilation mode.

Results for the same period of analysis inside the classroom are presented in Figure 5-5 below. The temperature varies from 27°C to 38°C over a day (15th June), as an approach it is quite interesting that natural ventilation could decrease temperature so significantly and for more temperature months, such as spring and winter, this could be a really good solution. Looking at these simulation results, it seems on average there is an 8°C to 10°C difference between the outdoor air and indoor air temperature.

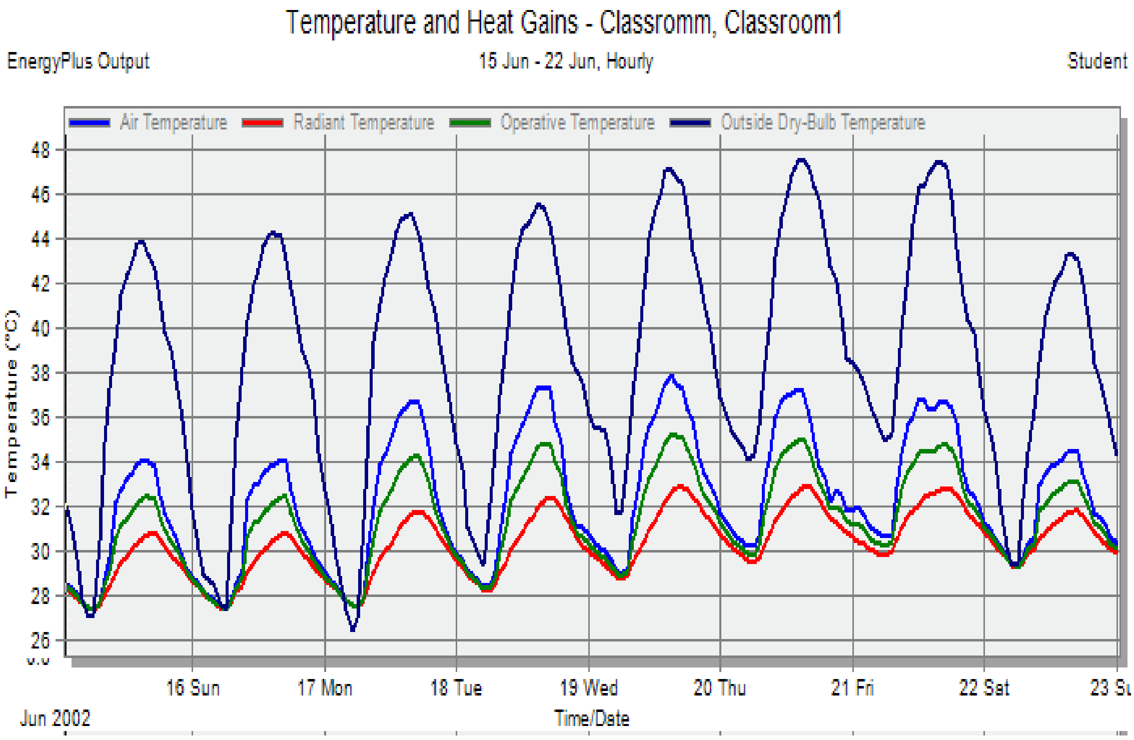


Figure 5-5: The classroom air temperature naturally ventilated with wind-catcher (ventilation only).

This lower temperature however is still on the high side from which one may expect the occupants to be not fully satisfied. Figure 5-6 shows the thermal comfort results usign the PMV indicator which clearly shows that are larger number of people would report a PMV of greater than 0.5, thus overall, the occupants would feel overheated. However this approach neglects the established fact that building occupants in natural ventilated and mixed mode buildings have a greater capacity to adapt according to their surroundings. The Fanger’s PMV model completely ignores this which makes the validity of Figure 5-6 questionable when assessing the thermal comfort for the wind-catcher system.

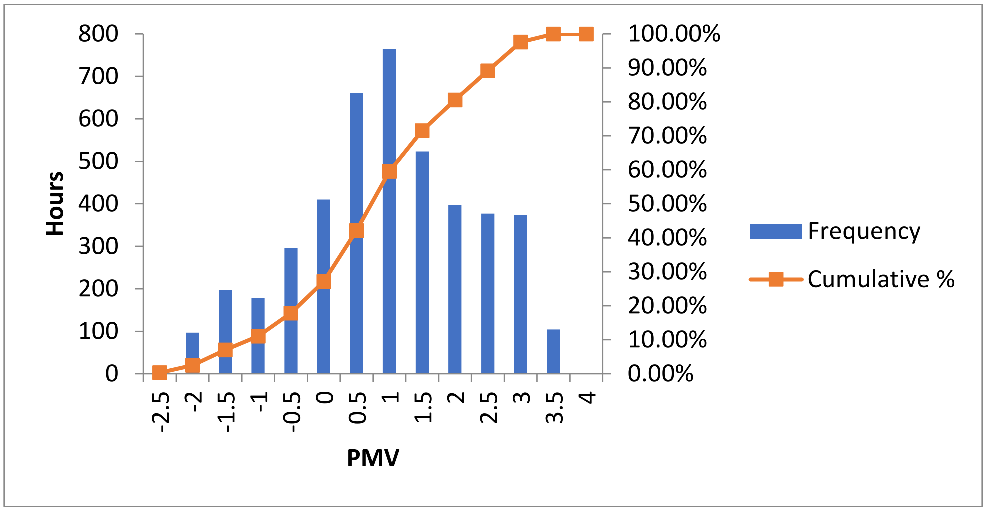


Figure 5-6: PMV Frequency Wind catcher Natural ventilation Case study (summer period).

For this reason, the thermal comfort has been analysed using the ASHREA adaptive thermal comfort model as follows – please refer to Section 3.3.2 for selection of comfort criteria. The adaptive comfort results for a typical summer day is shown in Figure 5-7.

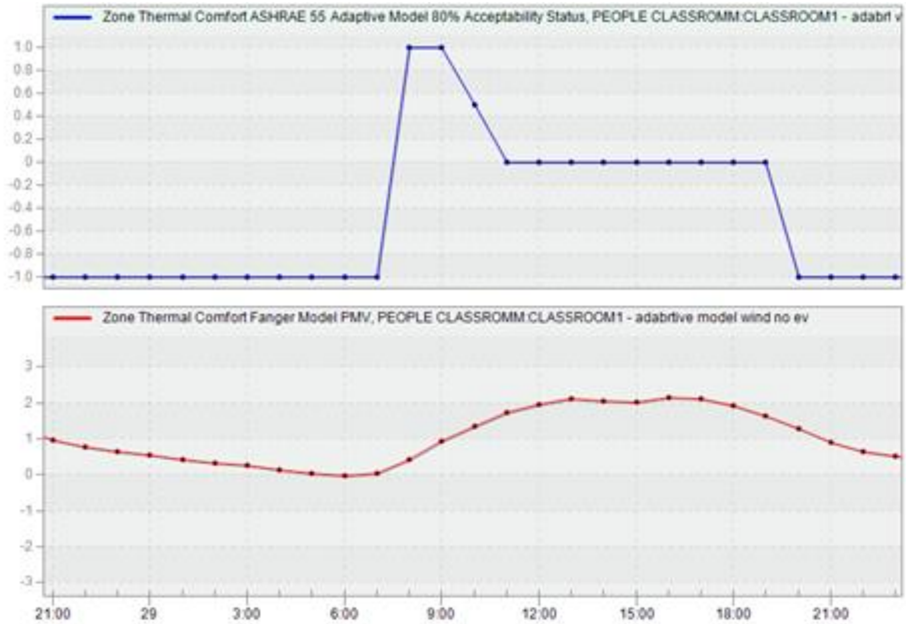


Figure 5-7 - Adaptive model results for a typical summer day (June 8th). Top: The ASHRAE 55 adaptive model 80% acceptability status shows that during the occupied hours, except for a couple of hours in the morning, the criteria is not satisfied. Bottom: While not applicable to natural ventilation designs, the PMV indicator is above 0.5 during the occupied period – which adds to evidence of discomfort in this scenario. These results show that the wind-catcher on its own is not able to provide thermal comfort in the indoor space for this scenario

In relation to Figure 5-7, the adaptive model has three output values (i) One – corresponding to indoor conditions that satisfy the 20% PPD criteria, meaning building occupants are comfortable (ii) Zero – uncomfortable indoor conditions (PPD % > 20) (iii) Minus One: Adaptive model cannot be calculated as the building is not occupied – and therefore this set of results should be neglected. From the figure it can be seen that before 9am and after 7pm, the output is either -1 or an invalid number (between zero and minus one). This is because the building is not occupied during this time and the correct calculation of the adaptive model is derived from the thermal comfort perceptions of building occupants. It can be seen that during the occupied hours, the model either predicts comfortable or uncomfortable. For this case with the wind-catcher's natural ventilation only, it seems that with the exception of some morning hours, the building is uncomfortable. The histogram for the whole summer period below shows how this option is not acceptable for adequate thermal comfort conditions. It confirms that for most of the summer, the conditions indoors are comfortable, with only 3% of the time building occupants feeling suitable satisfied with the indoor conditions.

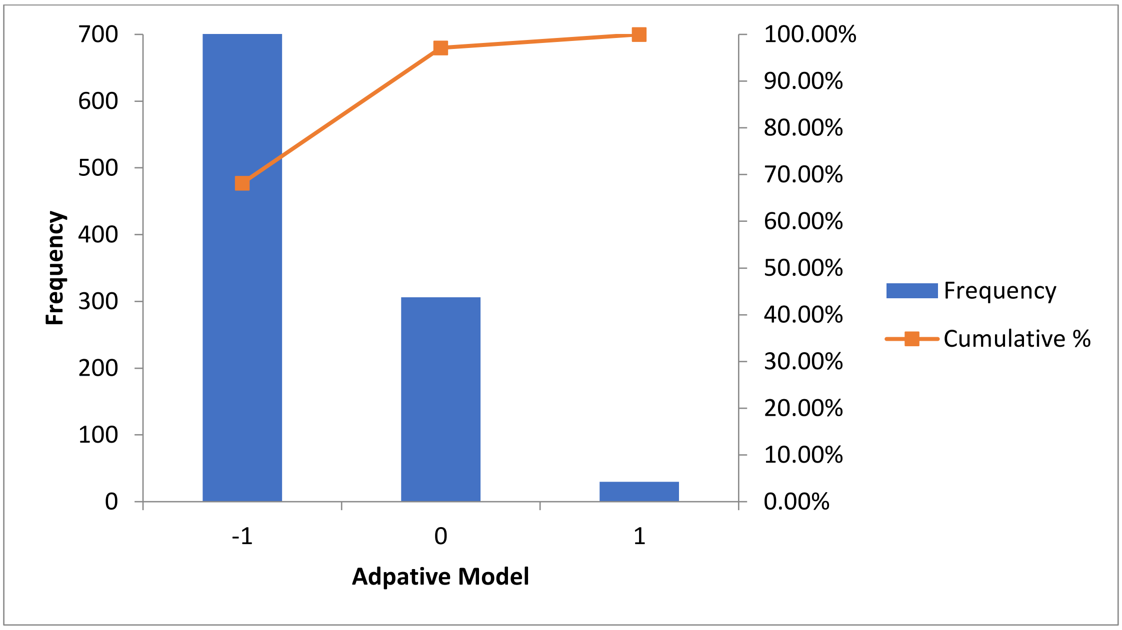


Figure 5-8 - Adaptive model results for Scenario 2 (wind-catcher only) – summertime. The value of minus one refers to unoccupied hours and is therefore neglected in the analysis. For the occupied hours clearly, for most of the time, the buildings occupants are feeling dissatisfied (97% dissatisfaction).

5.2.2 Winter period results

Within the winters, the temperature is much lower, in fact as shows by Figure 5-9 it ranges between 5 °C and 17 °C. The period of analysis chosen was 20 January to 26 Janurary, to represent the peak cold month in Kuwait. Within this time frame, the indoor air temperaure is shown to vary between 15°C and 22°C. Compared to the outdoor air temperature, again this is a signifcant lift in the air temperature as compared to the outside and may significantly reduce the cooling load of the building. However, temperature such as 15°C as expected not to be comfortable.

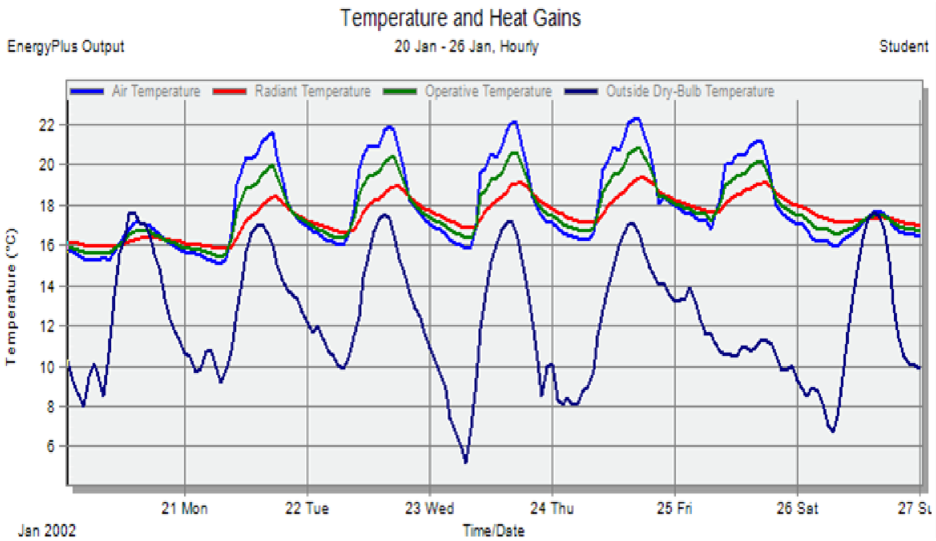


Figure 5-9: Wind-catcher temperatures in winter week.

As discussed in the summer months preceding section, for this natural ventialtion strategy, this PMV approach is not be suitable for this natural ventilation case. Therefore, the ASHRAE adaptive model of thermal comfort has also been used to assess the thermal comfort, as follows. The Figure 5-10 shows that this design is greatly successful for the winter period. Discounting the unoccupied period results, 188 values are predicted to be ‘0’ while 1356 values are predicted as ‘1’. This means that for the occupied period, 87.8% of the time, people would feel thermally comfortable indoors.

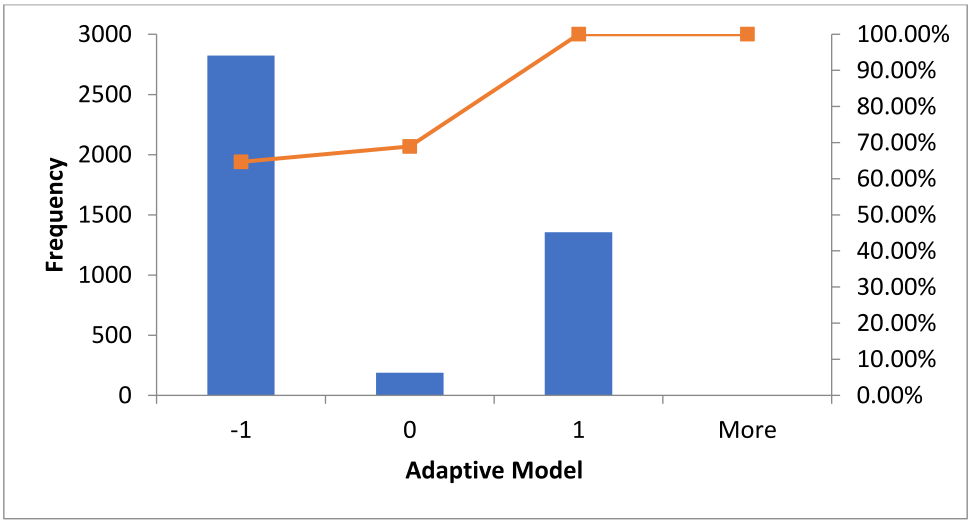


Figure 5-10 - Adaptive model results for wintertime Scenario 2 (wind-catcher only) – wintertime

Finally, as an additional tactice, the orientation of the classroom was varied in the software over a full rotation. This was done to assess the effect of wind direction on the thermal comfort. However, the wind direction did not have much difference on the results, showing that the wind direction had not effect on the wind-catcher's performance.

5.2.3 All year – scenario 2:

To assess this scenario's all year experience, the adaptive model's results are shown in Figure 5-11. Discounting the unoccupied time, 544 hours were reported as uncomfortable in comparison with 1584 comfortable hours. This equates to 66% of the hours being comfortable – with discomfort arising from the summer occupied hours.

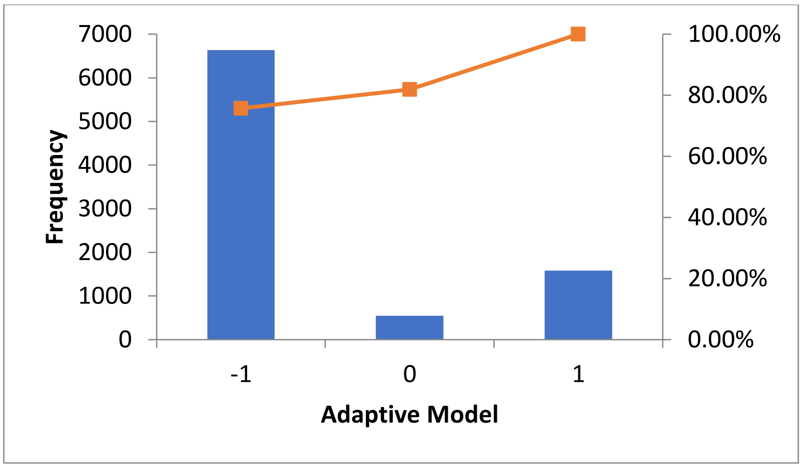


Figure 5-11 - Wind-catcher only natural ventilation all year results – Scenario 2

To assess the indoor air quality, the CO_2 levels within the classroom are simulated. Figure 5-12 and Figure 5-13 present the hourly and daily average CO_2 levels profiles for the whole year. From the figure, it is clear that the indoor is quality is well beyond 1100ppm, the threshold stipulated by ASHRAE for this case study. Figure 5-12 also shows that during the occupied hours, on average the indoor air quality with the AC off and wind-catcher only operation is unsatisfactory. Precisely**, 77% of the occupied hours had a CO_2 level above 1100ppm**.

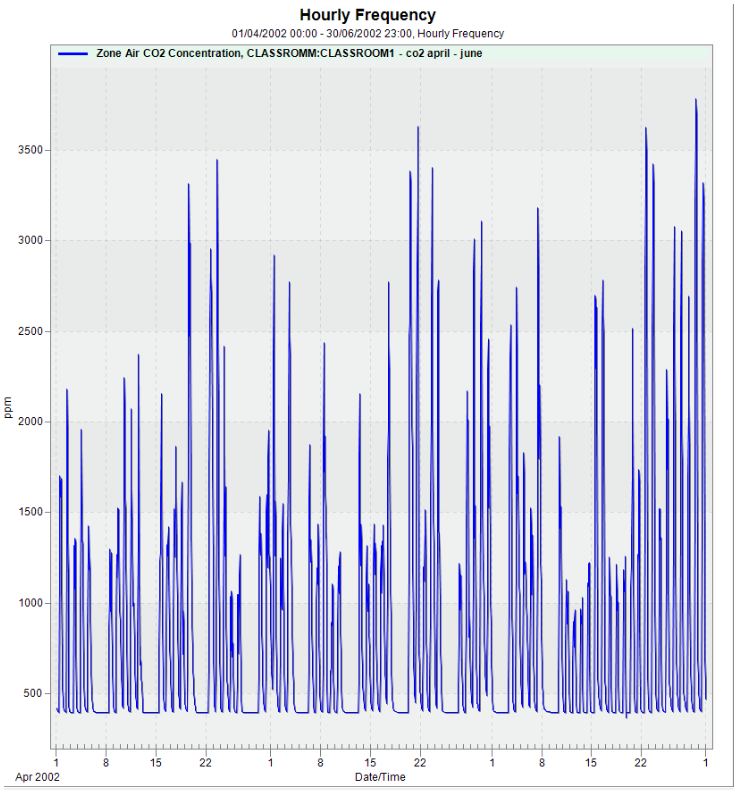


Figure 5-12: Hourly Co2 concentration inside the classroom for scenario 2

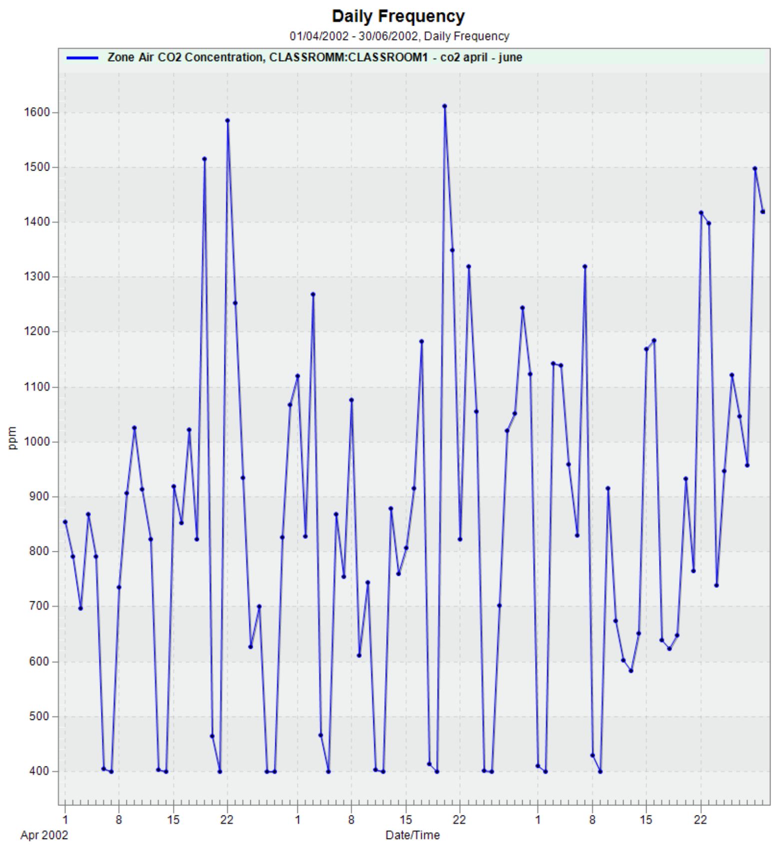


Figure 5-13: Daily Co2 concentration inside the classroom.

Finally, the air change rates for summer months of June-August is presented in Figure 5-14 (left). The air change range for the occupied hours hovers between 1.4 and 3.0. For the whole year, the average air change rate equates to 2.2 ach, as derived from Figure 5-14 (Right). This is considerably higher than the baseline scenario, and it clearly shows that the wind-catcher is operating as expected by generated higher air speeds in the classroom.

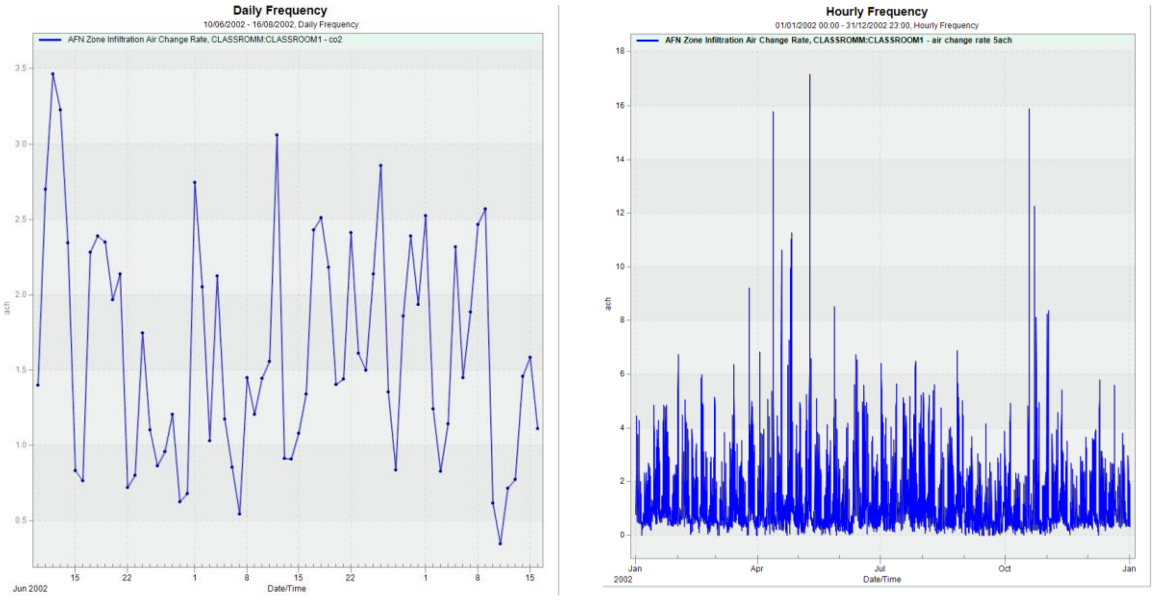


Figure 5-14: Air change rate for the wind catcher case without evaporative cooling. JUN-AUG. yearly avg. 2.2 ach (60.5 l/s).

5.3 Scenario three: Wind-catcher with evaporative cooling included

Similar to the previous section, the summer and winter months are assessed separately for scenario there as well. As this approach employed natural ventilation (the wind-catcher) together with mechanical evaporative cooling, thermal comfort is assessed through the ASHRAE 55 adaptive thermal comfort model.

5.3.1 Summer period results

The simulation period was kept the same to ensure consistency, which is the peak summer period of 15th June to 26th June. It should be noted that this was when the data was collected for model verification and validation. The results Figure 5-15 shows that the radiant temperature (which is often used as an indicator for thermal comfort), varied between 22℃ and 26℃ (Day/Night). This appears to be encouraging, as such temperature are likely to be considered comfortable.

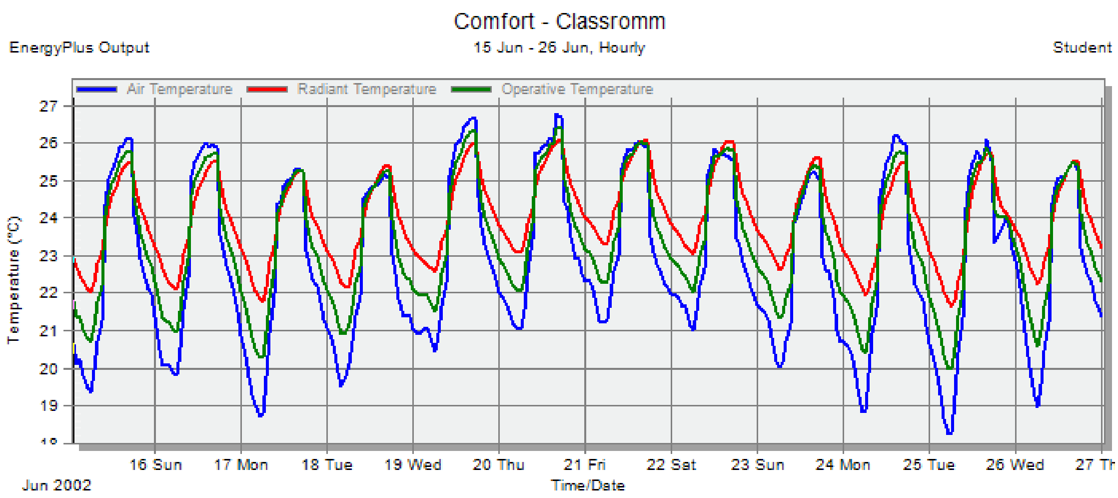


Figure 5-15: Classroom inside temperatures after applying the method – Occupancy Sunday to Thursday, 7am – 3pm.

From the results shown, the evaporative coolers provide an alternative cooling process. It can offer cooling while consuming only a considerably less amount of electrical energy for the operation as compared to an AC system (assuming electric fan).

The summertime adaptive model results for this scenario are very encouraging. Ignoring the unoccupied hours, only 8 values from a total of 342 summer hours analysed are uncomfortable. **This is 97.7% of the occupied hours being comfortable according to the international adaptive ASHRAE 55 model.**

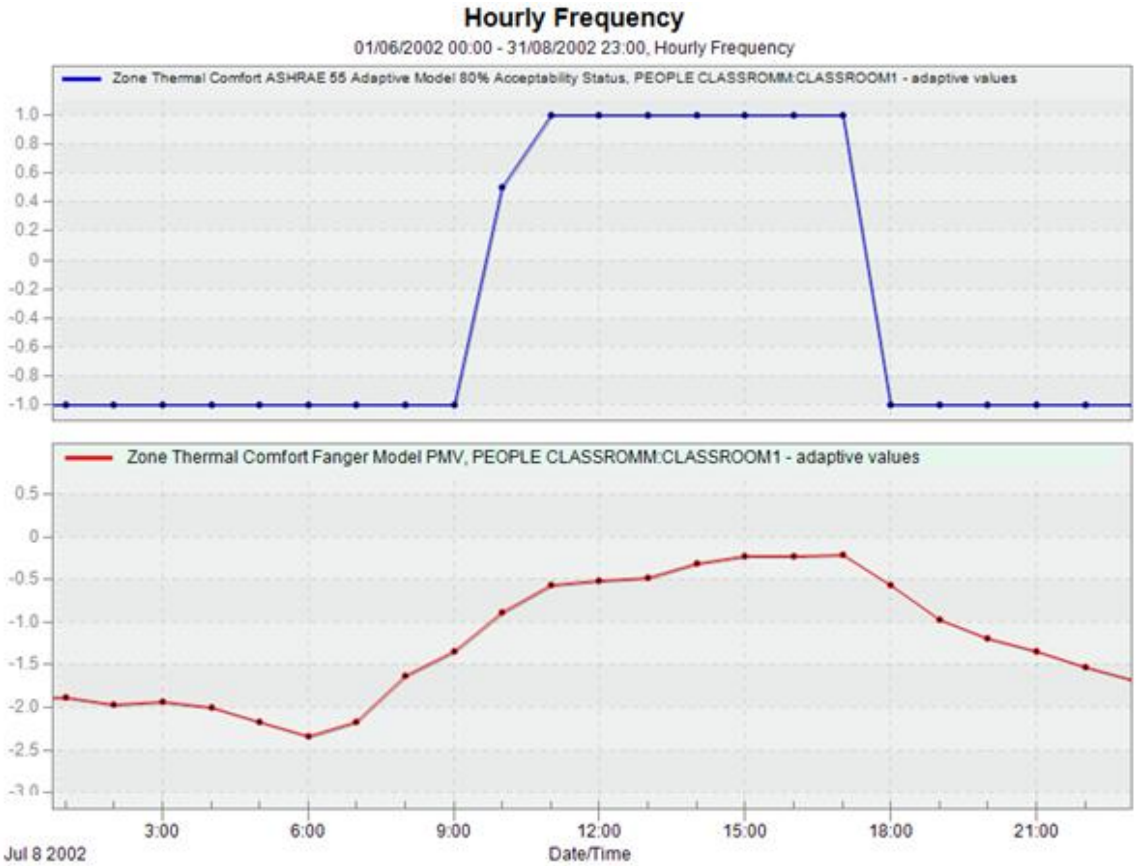


Figure 5-16 - Further analysis of the comfortable indoor conditions in summer for the wind-catcher with the evaporative cooler. Top: The simulation shows that the ASHRAE adaptive model 80% acceptability status is satisfied for almost all of the occupied hours during a typical summer day (June 8th). Bottom: The PMV indicator, although not entirely applicable to this natural ventilation scenario, shows absolutely no overheating perception (PMV is always less than +0.5). It should be noted that this plot is further evidence of the PMV model being unsuitable to assess this scenario, as it predicts overcooling, while such a thermal perception by the occupants is not suggested by the adaptive model.

5.3.2 Winter-time – Scenario 3

The performance of this option in the cooling case has also been analysed in the wintertime. The results show that this leads to significant overcooling of the building. Ignoring the invalid values, 1113 hours in winter are predicted to be overcooled (PMV < -0.5), which is **72% of the total wintertime occupied hours of the building** (Clearly, using the evaporator in the wintertime is not acceptable).

5.3.3 All Year Results

In this section, the all year performance of the wind catcher combined with the evaporative cooler have been presented. As the summertime results were promising for this case with the wind-catcher with the evaporator, the all year results are presented with added aspects as follows.

i. Thermal comfort (Adaptive ASHRAE 55 model)
ii. Energy use
iii. CFD analysis (air velocity and temperature distribution)
iv. Air quality

5.3.3.1 Thermal comfort:

For thermal comfort, Figure 5-17 shows the all year thermal comfort results for this case. The results show that the overcooling has a dramatic effect on the indoor comfort for this scenario, with uncomfortable hours exceeding those of the comfortable hours. Clearly, the evaporator should be kept off, which would all creating indoor winter-comfort conditions as in Scenario 2 – with 88% people feeling comfortable through using natural ventilation only. However, the main focus of this design is to reduce the cooling energy requirements in summer – which this design achieves to a higher level (98% acceptable comfortable hours). **For the whole year, with the evaporative cooler turned off for the winter, 86% comfortable hours are predicted through the simulation, with discomfort arising mainly in the winter season**. Figure 5-17 shows the zone mean rediant termperature prediction for the whole year. During the winter, it touches very low values (12C) – hence the high level of discomfort due to overcooling. However, in the summer, the indoor temperature does not exceed 26.5 C even in the peak summer conditions – hence leading to highly comfortable conditions in summertime.

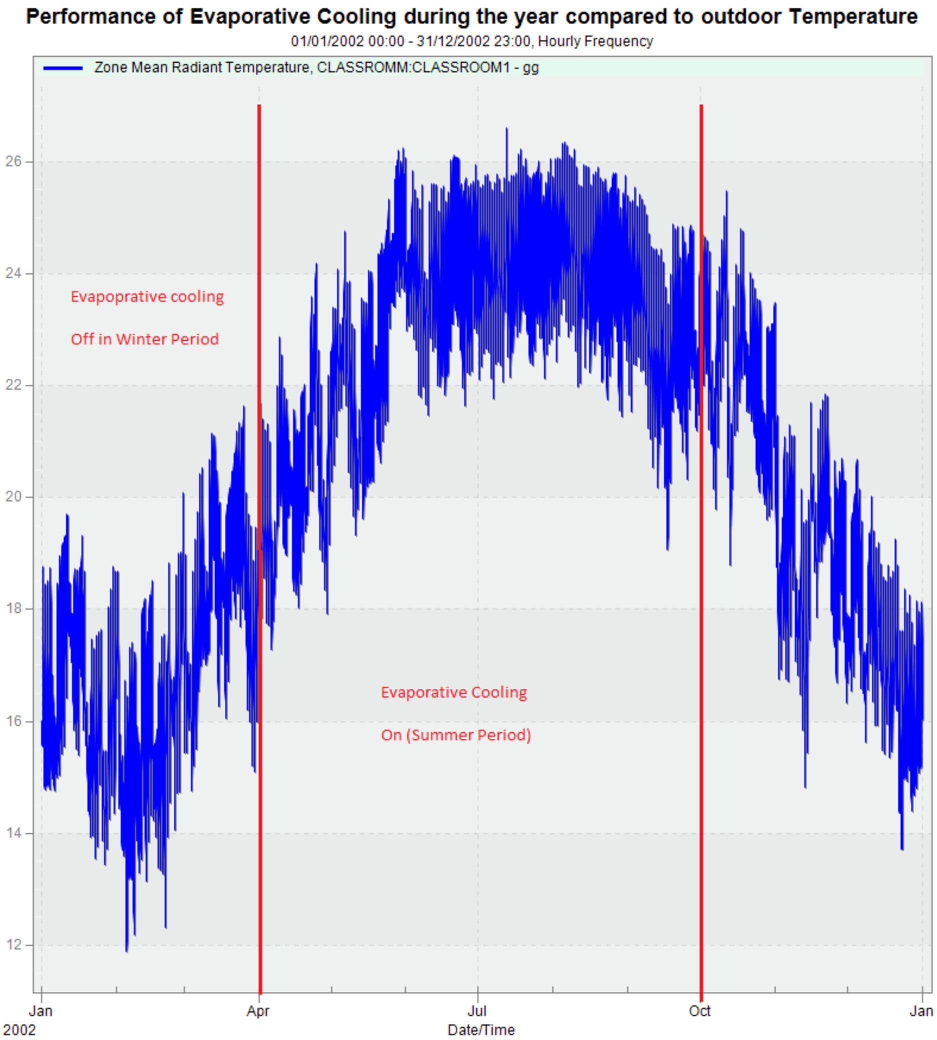


Figure 5-17: Mean Radiant Temperature (blue trace) of classroom (with Evaporative cooling) during all the year that corresponds to outdoor temperature (see Table 4-4).

5.3.3.2 Energy and water use:

The only electrical energy used with this design is only that of the fan for the evaporative cooler. The rated fan power for this design evaporative cooler design was 1875 kW along with water requirements of the evaporative cooler. As water is a rare commodity in the Kuwaiti desert climate, both the energy and water requirements along with the total cost based on current water and energy use tariff in Kuwait is presented in the following Table 5-1.

Table 5-1: Cooling demand and water consumption for the classroom for the summer period of analysis (April to September)

	Cooling energy demand [kWh]	Water [m3]	Water Cost [K.D]
Cooling	3514	27.6	4.862

It be seen in Table 5-1 that a net gross of 3514 kWh of cooling load consumes 27.6 m^3 as water requirements of the evaporative cooler. Based on the water cost in Kuwait for the governmental sector, water costs 0.800 Kuwaiti Dinar for each 1000 imperial gallons (4.5 L) (Ministry of Water and Electricity). Based on that rate it would cost 4.9 Kuwaiti dinar for 27.6 m^3 water.

5.3.3.3 CFD Analysis:

To understand the successful design at a greater detail level, a (computational fluid dynamics) CFD analysis has been conducted to examine the air speed distribution across the classroom in this scenario and is presented here. Design-builder software works with CFD RANS (Reynolds Averaged Navier-Stokes) modelling which is accepted to study the distribution of air speed and temperature. It uses the K-epsilon (k-ε) turbulence model. This model is one of the most widely used and tested of all turbulence models and is considered suitable for the objectives of this analysis. The boundary conditions used are that of the location of the school and weather data, the openings, the supply and extraction zones with 15th June 13:00 chosen as the typical summer peak afternoon snapshot. Figure 5-18 shows the convergence results for the CFD simulation. Before the results of the model can be generated, the CFD model has to reach convergence. This is depicted by the purple line, when it reaches a steady state level it represents reliability of the CFD results, which was in the study case 1800 iterations.

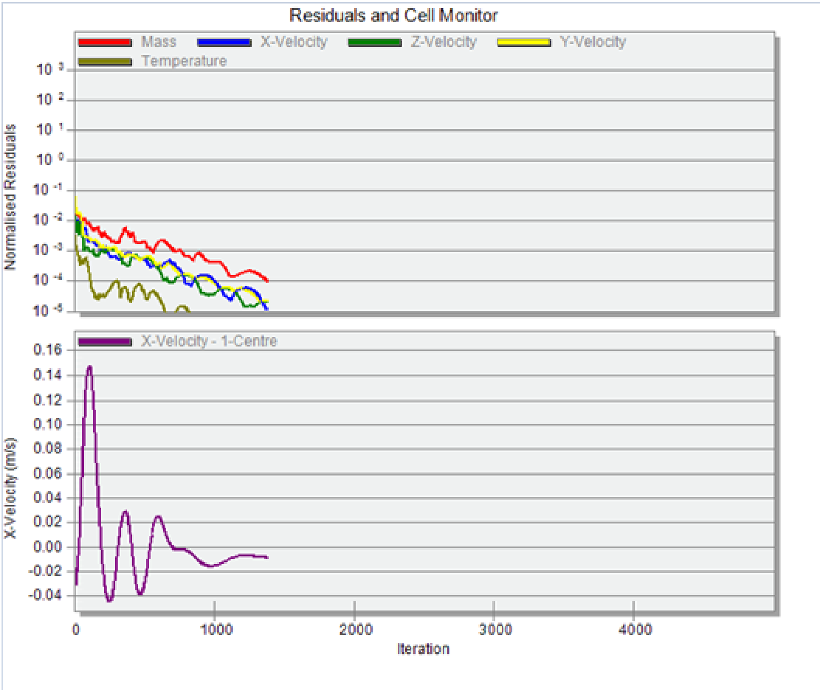


Figure 5-18: CFD Simulation process ending in Steady state line.

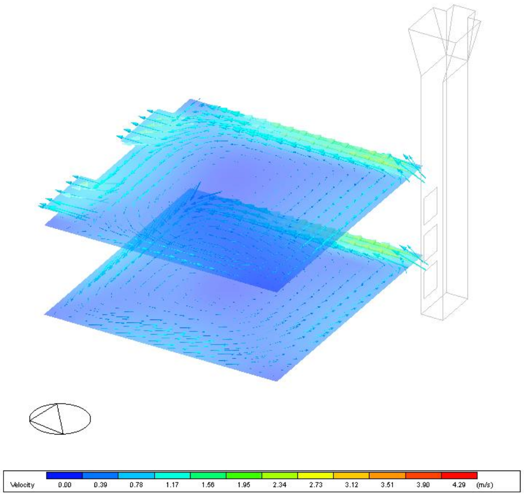


Figure 5-19: CFD designing tool shows the air movements inside the classroom (ventilation plus evaporative cooling).The heights cross sections are at 1.17m (seating level) and 2.5m (just above head height).

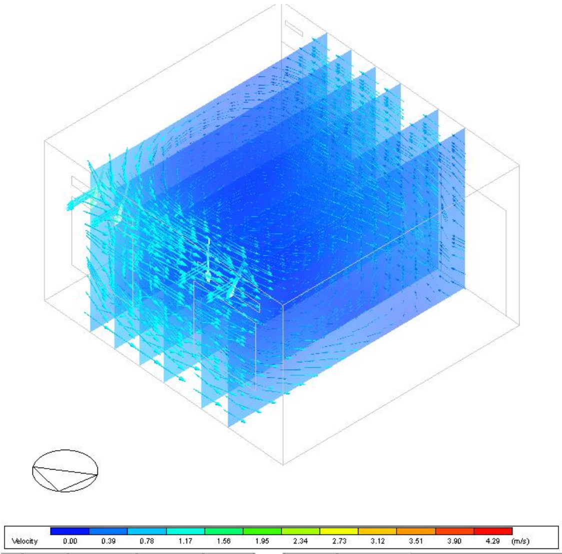


Figure 5-20: Air Velocity in the central area of the classroom.

Figure 5-19 and Figure 5-20 illustrate the air movements that are developed in the classroom due to the wind-catcher, in horizontal and vertical cross-sections respectively. The speed varied from 2.34 ms^{-1} to 0.39 ms^{-1} which is a good result in terms of human comfort as explained in literature complying with international ASHRAE standards (See section 2.1.11). Also, this CFD results shows the good design of the modelling prototype wind-catcher on how it drives air into the classroom, thus correctly utilizing the principles of ventilation in buildings. The window openings work as the important key in the natural ventilation as its size is important to develop a pressure difference for sufficient air flow in the classroom. The central air velocity inside classroom was indicated approximately to 0.78 *m/s* (Figure 5-21) which lies in the range of human comfort.

Air velocity distribution through a depicted or air-velocity contours is shown in Figure 5-21. It is clear that air flows across the classroom space showing good performance, utilizing the outside average wind speed. As design builder uses the RANS model, as described earlier, the resulting contour profile is based on averaged values. The contour velocity shows the concentration of air flow at the inlet side, then diffuses into the classroom space. Furthermore, Figure 5-22 and Figure 5-23 show the distribution of airflow in the classrom from the top view and in terms of air-velocity contours respectively. Both the figures provide additional confidence in the air flow conditions at the seating level, as in both cases, the air flow velocity was found to be between 0.39 $ms^{-1}$and 0.78ms^{-1}, at the height of 1.17 m from the ground approximately at the occupants seating level, which is within the comfort limits prescribed by ASHRAE 55.

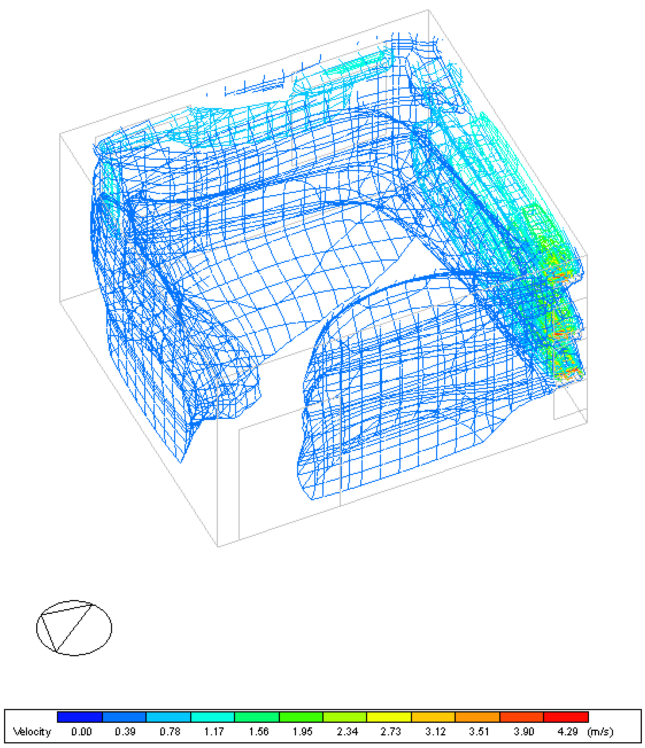


Figure 5-21: Air Velocity contour at the classroom space (designbuilder).

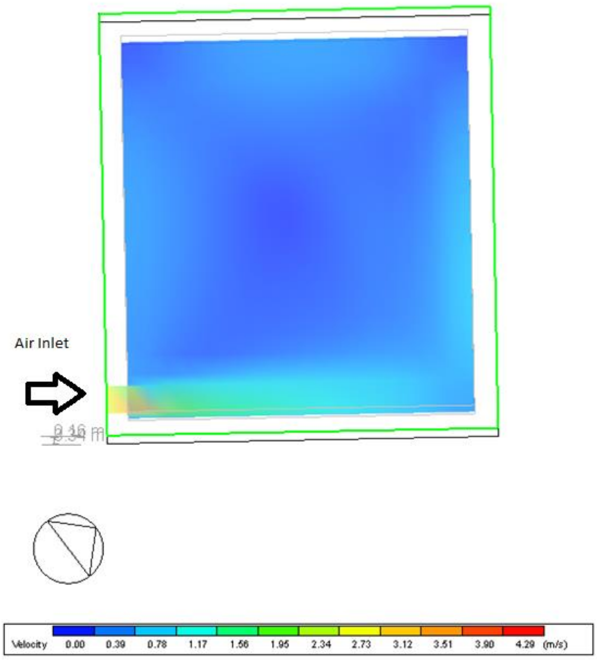


Figure 5-22: Top view Cross-section showing the air flow diffusion in the classroom at 1.17m height (seatinglevel).

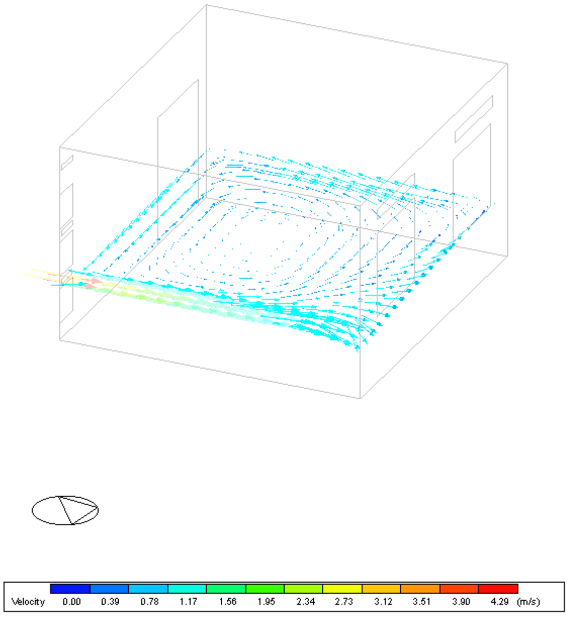


Figure 5-23: Air velocity contours showing distribution and direction of air at the seating level (1.17m) of the occupants in the classroom

For CFD analysis related to temperature distribution in the classroom, Figure 5-24 is presented below. This analysis has been conducted for time snapshot selected from a typical summer week, between 15 – 22 June. Specically, this show the snapshot for 15th June at 13:00 in the afternoon, which are peak summer conditions – thus testing the design proposed in this thesis to the maximum. The results show a steady state distribution across the classroom with 20.13 º C in this summer period Figure 5-24.

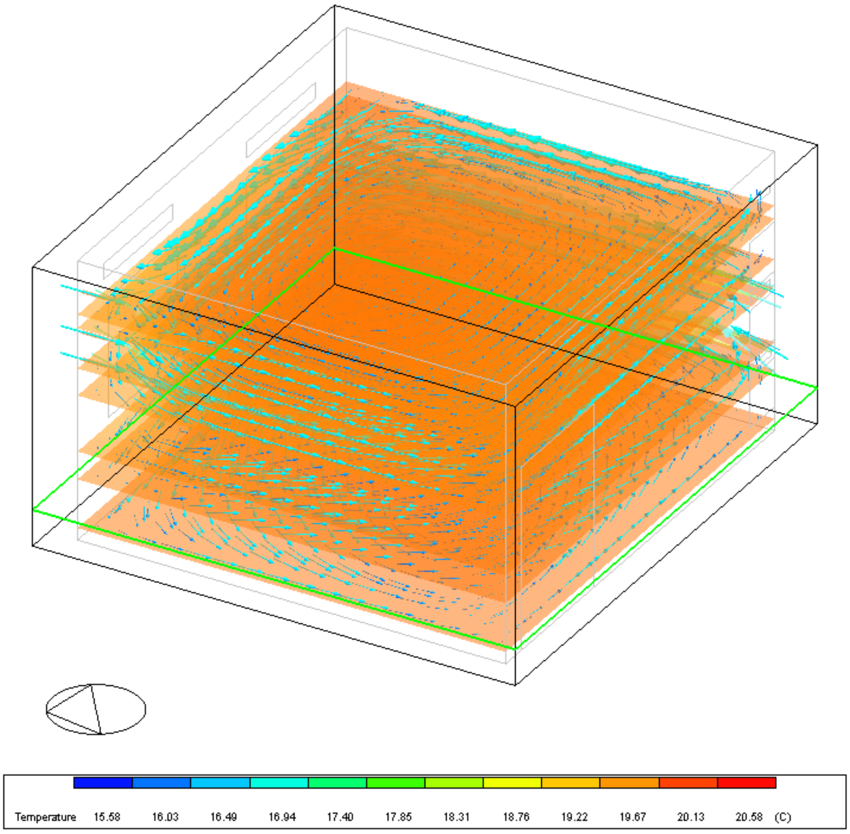


Figure 5-24: Temperature Distribution inside the classroom in the scenario 3, summer afternoon period (typical week: 15th June, 13:00)

Overall, the temperature varies from 17.4 °C to 20.12°C, based on which good thermal comfort is expected. This equilibrium of temperatures is been predicted due to high sealant, AAC block and thermal wall coat (thin layer of thermal paint from the company (NCP) in Kuwait). Further analysis at the seating height is shown in Figure 5-25 revealing that at occupant hieght of 1.17m, the temperature is at 19.22C – again coresponding to hight levels of thermal comfort. Finally, Figure 5-26 shows the temperature variation in the classroom for the three peak summer months, June, July and August. Here, the temperature inside the classroom was found to be in the rage of 25 °C ± 0.5°C. Based on these results, it is clear why the adaptive model is showing highly comfortable conditions (98% of acceptable hours). Even though the PMV model is excessively stringent for NV building, and hence is not applicable, even the PMV results are acceptable for this case. The PMV model was shown to predict occupant sensation between -0.41 to -0.29 in Figure 5-27. This is certainly in the comfort zone for Kuwaiti population, as the study Al-Mutawa *et al*. (2004) showed that Kuwaiti school building occupants found PMV ranging -0.5 to 0 the most comfortable, with a neutral temperature of

24°C. In conclusion, the various CFD based analysis confirms the highly comfortable conditions predicted for scenario 3 (wind-catcher plus evaporative cooling).

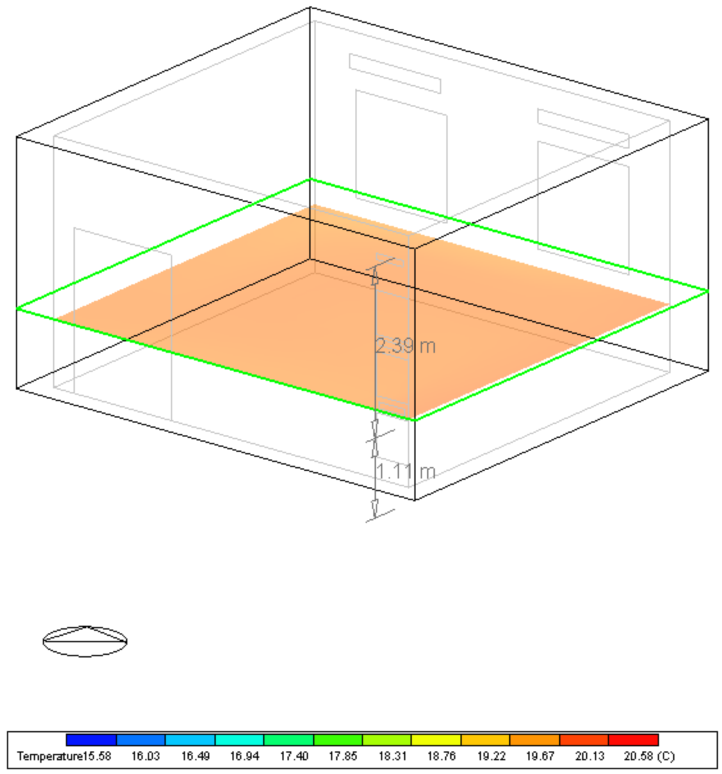


Figure 5-25: Temperature distribution at the seating level of the occupants inside the classroom.

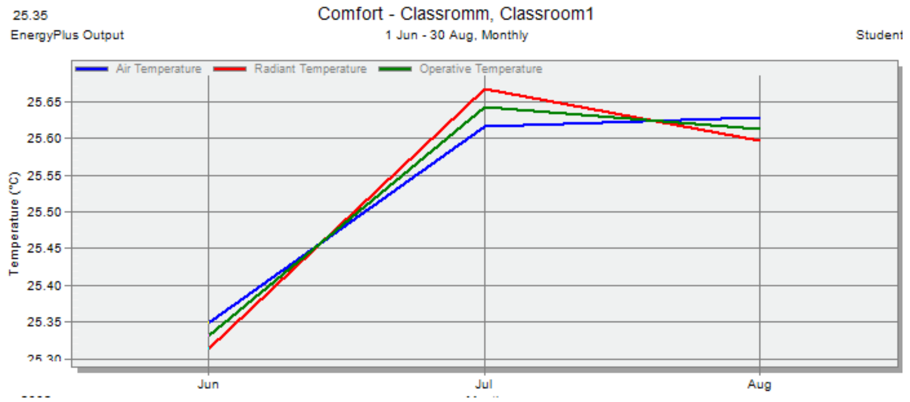


Figure 5-26: Temperature monthly report inside the classroom subset- period (Jun-Aug)

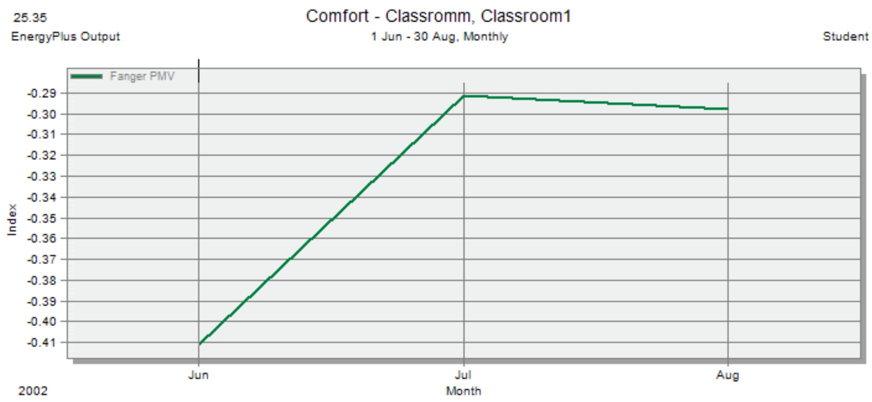


Figure 5-27: Average PMV model for the classroom for the hottest period in summer.

5.3.3.4 Air quality assessment - Carbon Dioxide Concentration Results

As discussed previously, according to ASHRAE, the recommended CO2 level in classrooms should be no more than 700 ppm above outdoor air. Since outdoor air is approximately 400 ppm, indoor CO2 levels should be no more than 1,100 ppm. However as shown in the baseline scenario, AC cooling only, while the thermal comfort is achieved, the CO2 levels are almost all the time above this level during the occupied periods of the school (Figure 5-28).

The use of the wind-catcher along with the evaporator not only has been able to reduce the energy use and provide satisfactory thermal comfort, but in fact, shows that the CO2 levels with this design are also within the prescribed ASHRAE limits (ASHRAE standard 62.1-2016). The results showed that CO2 concentrations to be below the recommended level of 1100 ppm for the daily average in the hottest months of June and July (650 ppm to 900ppm). Additionally, the average was found 692 ppm for the occupied period only in June for the classroom. The predictions from the simulations show that the CO_2concentration was varying between 450 ppm to 1100 ppm during the day. Specifically, based on the hourly simulation, **90% of occupied hours is expected to have a CO_2 levels below the 1100ppm threshold.**

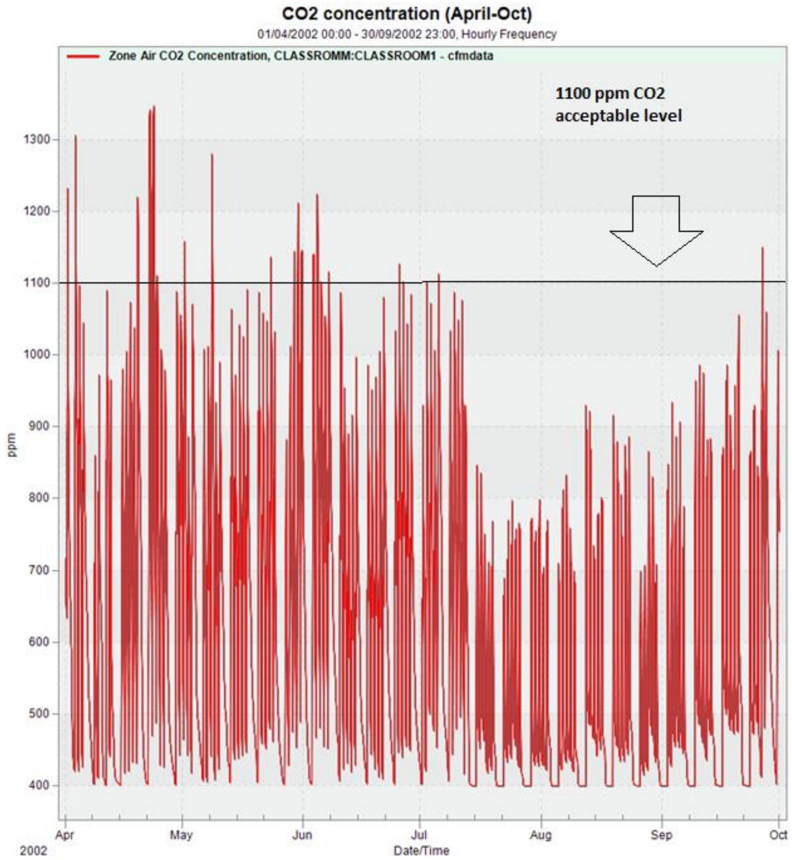


Figure 5-28: Simulated hourly CO2 concentration for the period (April - September) – Scenario 3 (Wind catcher plus evaporator).

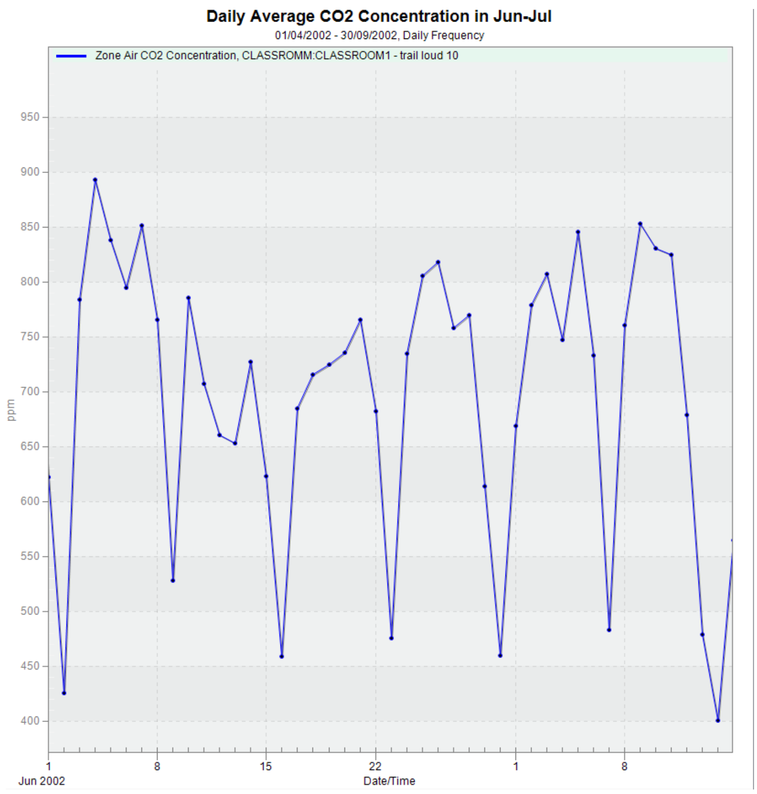


Figure 5-29: CO2 concentration for the period of (June – July).

5.3.4 Air Change Rate Results

To ensure consistency in presenting results, the air change rage for a typical week in June, followed by the whole year are provided in Figure 5-30 and Figure 5-31 respectively. The weekly results show that the air change rate has significantly increased from 2.2 ach (60.5 l/s) in the case without the evaporative cooler, and it hovers above 7ach in this scenario. The yearly average for these scenarios as depicted in Figure 5-31 results in a value of 6.95 ach (191.13 l/s).

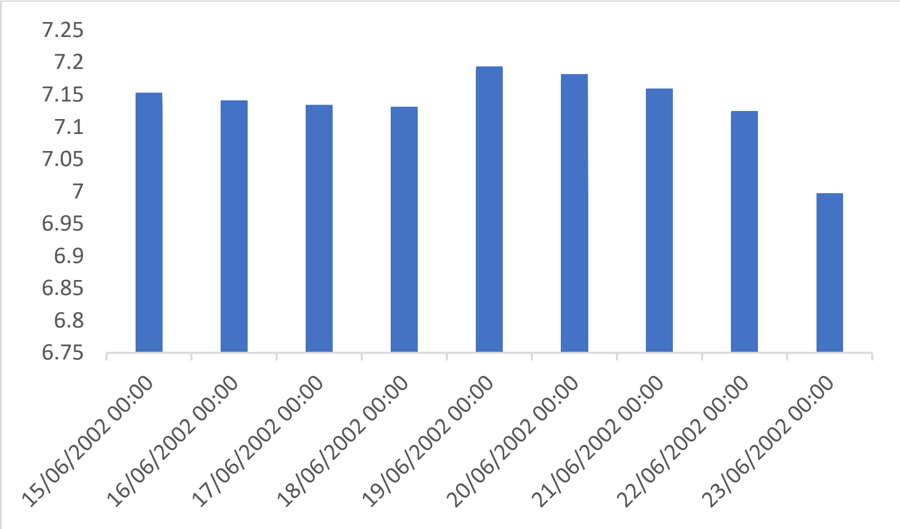


Figure 5-30: Daily average occupied hours air change rate for a typical week in June (15th - 22nd). The air change rates have increased significantly over scenario 2 as the evaporative cooler fan pushes more air through the building.

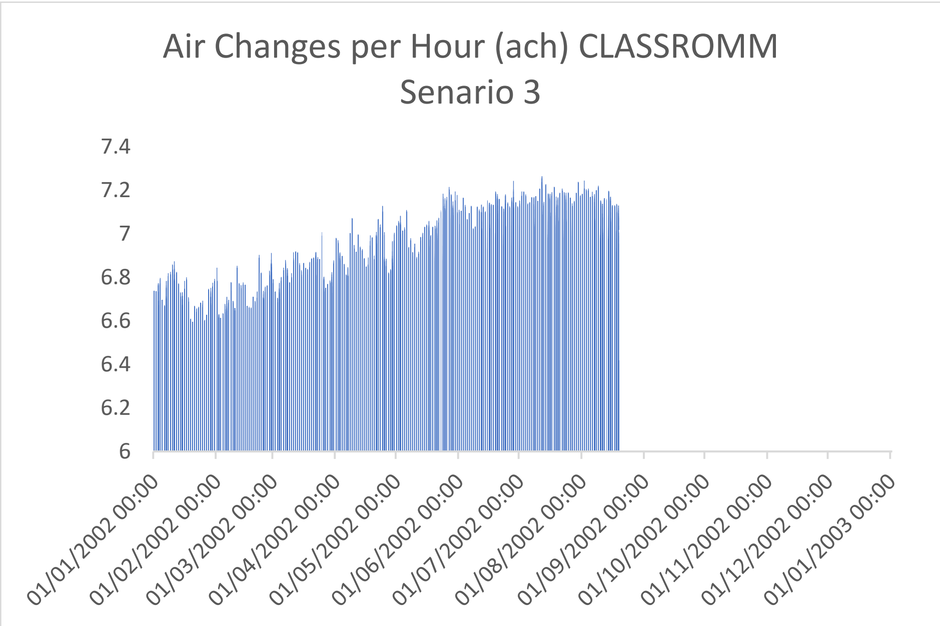


Figure 5-31: All year air change results for Scenario 3, resulting in an average value of 6.95 ach (191.13 l/s).

5.4 Scenario four: Wind-catcher with evaporative cooling plus A/C for backup

As initially proposed in the research design, the final scenario include the use of the A/C system along with the wind catcher design to see if any improvement in thermal comfort is achieved. The backup AC system is simulated to come online when the threshold of 27.5 ºC indoor air temperature is exceeded.

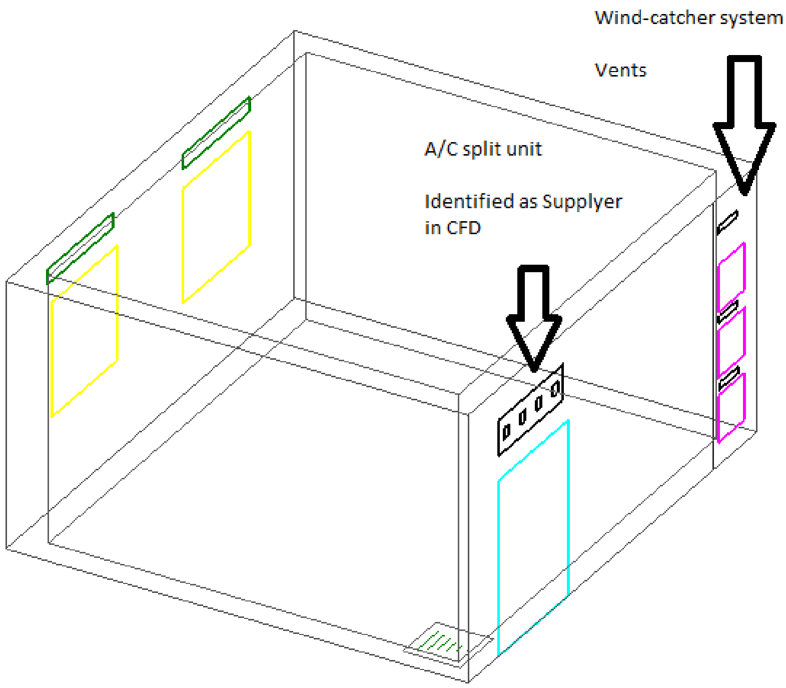


Figure 5-32: Classroom case study (A/C split unit + Wind catcher evaporative cooling).

Figure 5-32 shows the boudnary conditions and systems are modelled in the DesignBuilder software. The PMV frequency chart in Figure 5-34 shows worsened thermal comfort as compared to Scenario 3. It can be seen that for the all year analysis, the building is significantly overcooled. Both the thermal comfort metric, the Fanger's PMV and adaptive model show that building occupants are uncomfortable for the majority of the time. Only 52 votes were in the PMV comfort range for the static PMV model, out of a total of 365 votes, which is only 14.2%. **Therefore, only 14.2% of the time, the building occupants are expected to be comfortable based on the ASHRAE PMV model criteria**. The possible reasons for this are described in the following chapter in which an analysis and discussion on the results is provided. With regards to indoor air quality, the CO2 levels are below the 1100ppm threshold 100% of the time, as evident from Figure 5-35

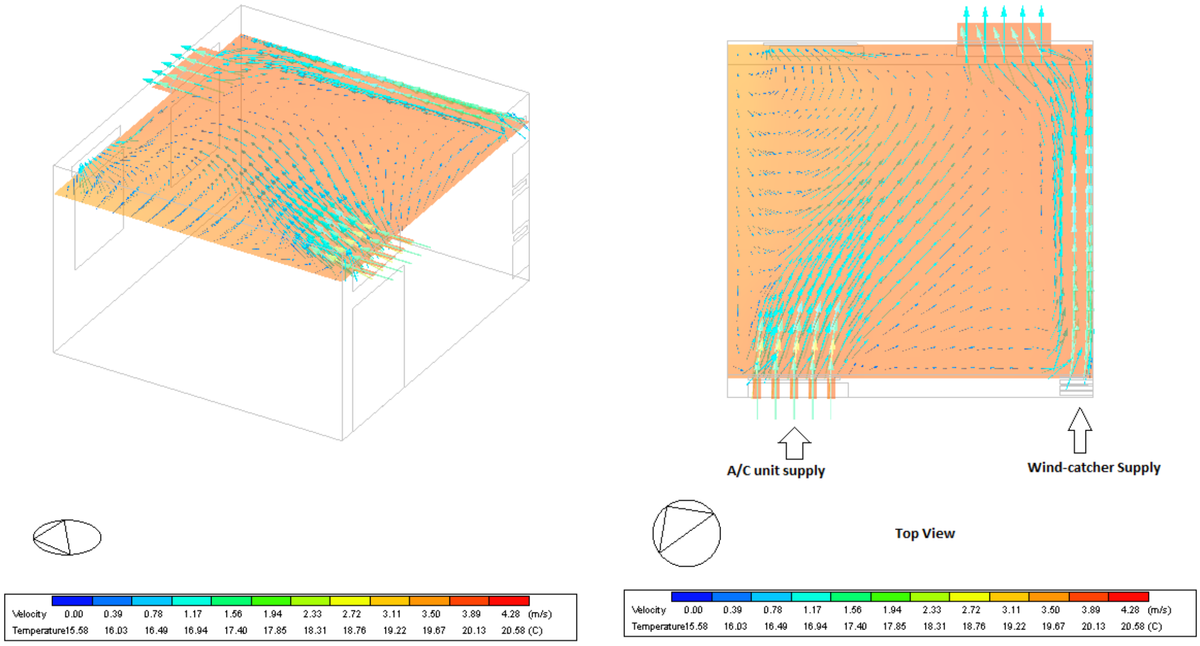


Figure 5-33: Velocity and temperature distribution for (A/C and evaporative cooling case study).

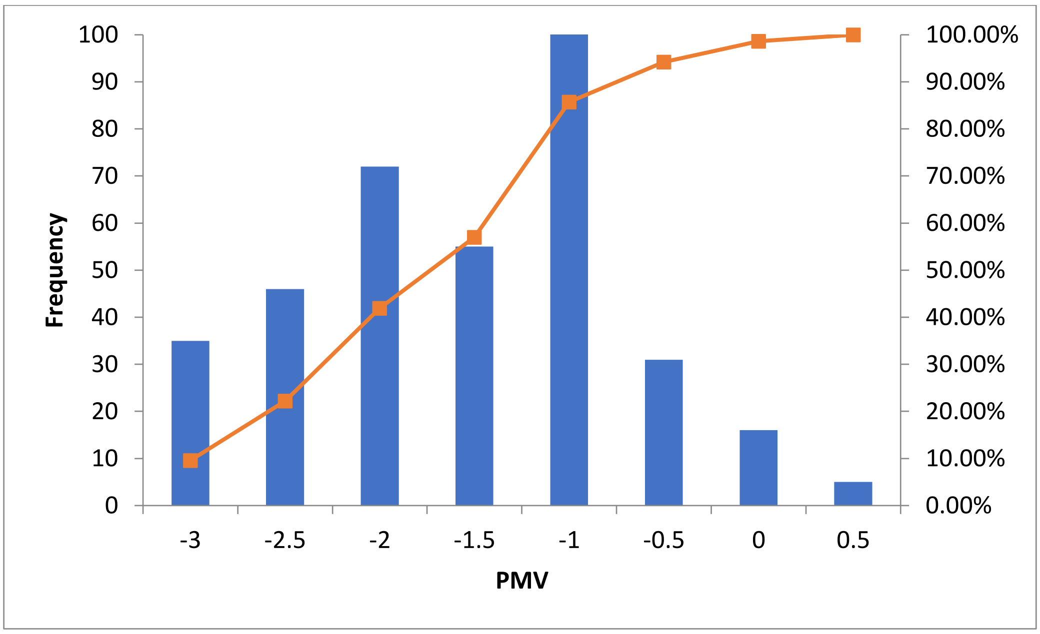


Figure 5-34: PMV model for A/C + wind-catcher Evaporative cooling case Scenario 4 – all year analysis. Considering that this is a mixed mode building, the PMV results are applicable and suggest significant overcooling (PMV < -0.5 suggests overcooling). This is possibly due to the fact that the elevated air speeds due to the wind-catcher leads to comfortable temperatures at higher indoor air temperatures as compared to the case without the wind-catcher.

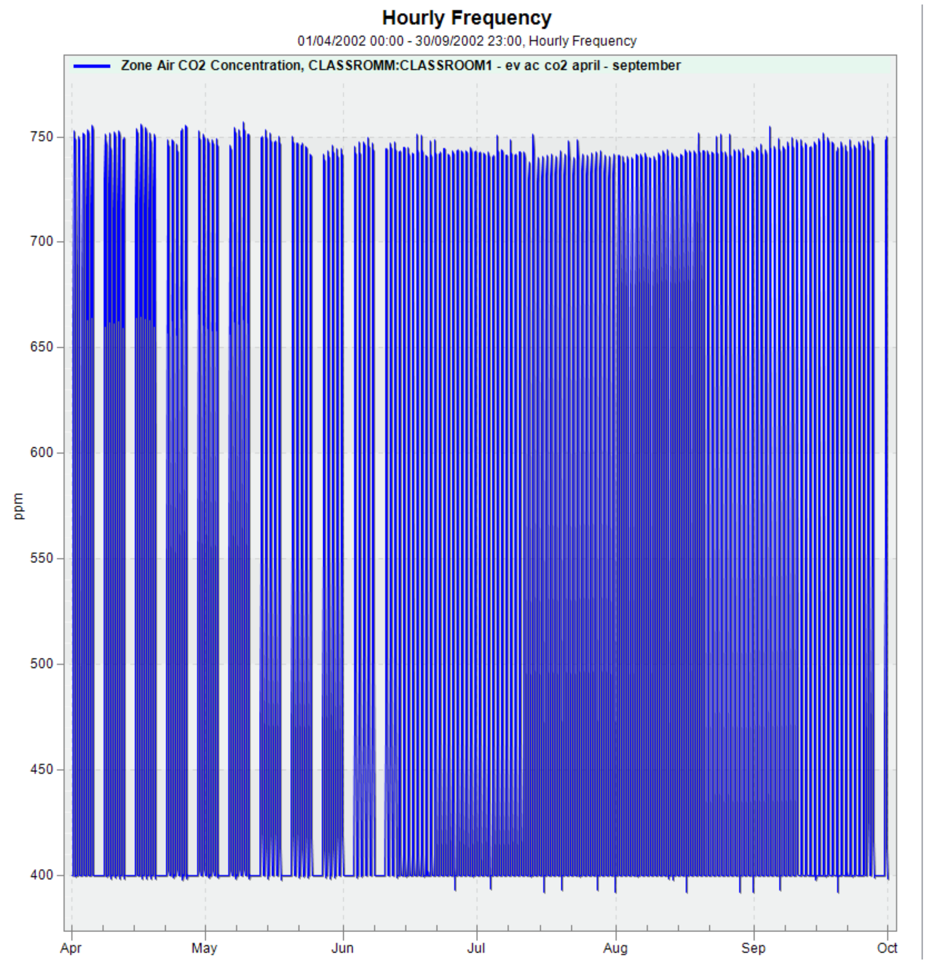


Figure 5-35: Co2 concentration for scenario 4 (April to September). It is clear that for this case, the CO2 levels stay well below the 1100ppm threshold.

The yearly air change rates are depicted in Figure 5-36, showing a similar range as in the previous scenario. The yearly average value as derived from this data is 6.86 ach (188.65 l/s), a slightly lower value. This can be attributed to the fact that when the AC is operating, the evaporative cooler turns off and the air flow drops slightly – hense a reduction of 0.09 ach over the year as compared to scenario 3.

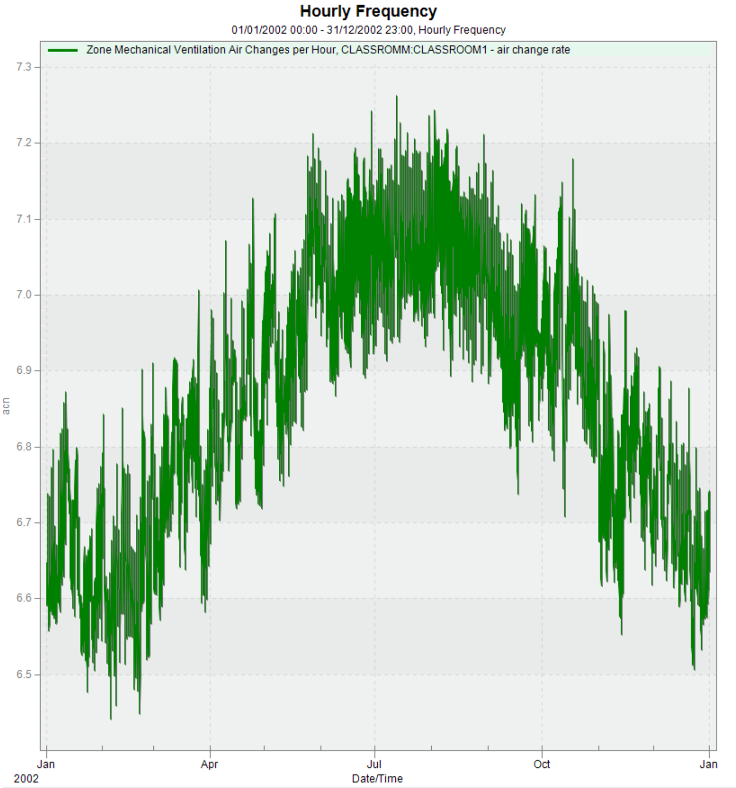


Figure 5-36: air change rate for the classroom scenario 4 – leading to an average value of 6.86 ach (188.65 l/s).

5.5 Results overview:

In this section, an overview of the results is provided to generate a holistic view of the results that have been presented in this chapter. This is summarised in Table 5-2 that presents the annual energy consumption in kWh, the indoor air quality as % occupied hours below the ASHRAE stipulated threshold of 1100ppm, all year thermal comfort based on Fanger's PMV and the ASHRAE adaptive thermal comfort model, and the water use in meter cubed. Table 5-2 makes it clear that scenario 3 (wind-catcher plus evaporative cooler) fulfils the thermal comfort criteria at the lowest energy whilst improving air quality and reducing energy use form the baseline by 13542 kWh (53%) at the expense of 27.6m^3 water requirement. The air flow in each scenario is represented through the air change rate analysis in each case – that align with the thermal comfort and CO_2 results. In scenario 1, the yearly average air change rate is the lowest at 0.85 ach (23.375 l/s), followed by an increase to 2.2 ach (60.5 l/s) in scenario 2 due to natural ventilation developing from the wind catcher. The air change rate is maximum in scenario 3 at 6.95 ach (191.13 l/s), followed by a similar value in scenario 4 (6.86 ach = 188.65 l/s). These results are further discussed to draw out conclusions in the following chapter.

Table 5-2 - Results Summary table comparing the different scenarios

	Baseline (AC cooling)	**Scenario 2 (Wind-catcher)**	**Scenario 3 (Wind-catcher with evaporative cooling)**	**Scenario 4 (Wind-catcher with evaporative cooling with A/C backup)**
Annual Energy consumption (kWh)	25406	None (100% reduction - NV)	11864 (53% reduction)	11553 (55% reduction)
Annual % occupied hours below 1100 ppm CO_2	20%	23%	90%	100%
All-year Thermal Comfort	PMV: -1 to 1.5 Discomfort = 28%	Adaptive ASHRAE Discomfort = 34%	Adaptive ASHRAE Discomfort = 14%	PMV: -3 to -0.5 Discomfort = 86%
Annual Water Usage (m^3)	0	0	27.6	27.6
Annual Average occupied hours air Change rate	0.85 ach	2.2 ach	6.95 ach	6.86 ach
Fresh air l/s	23.375 l/s	60.5 l/s	191.13 l/s	188.65 l/s
Fresh air l/s/p (29 occupation)	0.81 l/s/p	2.09 l/s/p	6.59 l/s/p	6.5 l/s

Chapter 6 – Discussion

6.1 Introduction

In this section, the results presented in the previous chapter are analysed to develop an understanding of the strengths and limitation of the wind-catcher based design for school buildings, and to inform future directions of research or practical application.

6.2 Discussion

The primary gaol of this project was to develop an NV based cooling strategy that could provide satisfactory thermal comfort whilst improving the energy efficiency of the cooling system. Before each scenario is analysed and discussed, an overview results presented Table 5-2 are first discussed.

Thermal comfort in scenario 3 (wind-catcher plus evaporative cooling) has been simulated to be highly acceptable, not only comparable but in fact an improvement over the baseline where the school is cooled through air-conditioning only. For the baseline, the Fanger's PMV indicator is suitable for assessing the thermal comfort as it is HVAC based conditioning. For scenario 3, the building can be considered naturally ventilated, thus Fanger's PMV to gauge the thermal comfort of occupants was not acceptable. Using the adaptive ASHRAE model for scenario 3 and Fanger's PMV for the baseline, the discomfort percentage votes were 14% and 28% respectively. This is a significant improvement over the baseline in terms of thermal comfort. Additionally, this was accompanied by a drastic 53.3% reduction in energy use. Compared to the baseline scenario where the school is cooled using AC air conditioning only, the wind-catcher with the evaporator is simulated to consume 13542 kWh less energy per year – making this design highly efficient whilst providing improved thermal comfort by an additional 14%.

In addition to improving thermal comfort and a substantial reduction in energy demand, indoor air quality is also dramatically affected. According to ASHRAE, the recommended CO2 level in classrooms should be no more than 700 ppm above outdoor air. Since outdoor air is approximately 400 ppm, indoor CO2 levels should be no more than 1,100 ppm. Referring to Table 5-2, this NV based design in scenario 3 also improves the air quality as compared to the baseline – by having only 10% of the occupied hours above this threshold, whereas for the baseline 80% occupied hours are predicted to have a CO_2 level above 1100ppm.). This can be attributed to the higher air change rate achieved with this design, which is a yearly average of

6.95 ach (191.13 l/s) as compared to 0.85 ach (23.375 l/s) in the baseline scenario. For a highly populated room such as a classroom, indeed such high air change rates appear to be a necessity to ensure health indoor conditions. Therefore, Scenario 3 – the wind-catcher with evaporative cooling is predicted to achieve significant improvement over the baseline AC air-conditioning scenario with regards to (i) thermal comfort (ii) energy use (iii) indoor air quality. However, the evaporative cooler utilized is predicted to consume water; 26.7 m3 for the summer season. However, this demand of water is not considered a significant drawback, costing 4.6 Kuwaiti Dinar for a summer season. In summary, **the wind-catcher plus evaporative cooler is the scenario that delivers high thermal comfort, high indoor air quality and drastically lower energy use.** Having established the improvement of the best-case scenario 3 over the baseline, each scenario is now analysed and discussed to develop a deeper understanding.

6.2.1 Baseline (Scenario 1):

This is the typical case found in practice in Kuwait schools, and perhaps indeed in the wider GCC region. In the hot desert climate, thermal comfort is achieved using air-conditioning only. The results for this baseline scenario made it clear that for the classroom, this does not only fall short at providing thermal comfort (72.1% of the total time is comfortable), but in fact also leads to poor indoor air quality (CO_2 ranging between 2000-4500ppm) and low air change rates of 0.85 ach (23.375 l/s) averaged over the year. This is mainly attributable to the fact that the classroom has 29 students and 2 staff in this analysis, and therefore the internal gains impact indoor air temperature, while the CO_2 from the buildings occupants raises the levels to beyond the threshold of 1100 ppm stipulated by the ASHRAE standard 55.These are serious issues that addressed through the natural ventilation design presented in this thesis. In summary, **the baseline AC cooling mode only leads to considerable discomfort in peak summer conditions, poor indoor air quality at the cost of significant energy use in operating the cooling systems.**

6.2.2 Scenario 2:

In this scenario, a wind-catcher to operate in complete natural ventilation mode is to provide the indoor thermal comfort. From the results, it seems that the summertime cooling was highly ineffective, as 97% of the time the building occupants are expected to be uncomfortable, based on the adaptive AHRAE 55 standard for thermal comfort. It should be noted however that for the wintertime, this design resulted in 88% of comfortable time, thus drastically reducing the need for building heating during the winter. Additionally, the CO_2 daily ranged dropped well below the 1100 ppm threshold, thus solving the problem of indoor air quality with the baseline scenario 1. This was achieved through elevation of the air change rate form 0.85 ach (23.375 l/s) in the baseline to 2.2 ach (60.5 l/s), averaged of the entire year. This design does consume some amount of water in the evaporative cooling process; however, this resource use is negligible when compared to that of the energy used for cooling. In summary, **the wind-catcher design is predicted to provide satisfactory thermal comfort only in wintertime, whilst drastically improving the indoor air quality and zero energy use for building conditioning (natural ventilation).**

6.2.3 Scenario 3:

In this scenario, the wind-catcher is facilitated by an evaporative cooler. This scenario has a dramatic impact on all parameters considered. Thermal comfort improves to only 2% discomfort time, with a reduction in energy use by 53.3%, while reducing the indoor CO2 concentration to well below the 1100ppm threshold stipulated by ASHRAE. The air change rate further increased in this scenario to 6.95ach (191.13 l/s) averaged over the year. However, the winter thermal comfort was badly impacted, as 72% of the time, the building occupants are expected to be overcooled. This issue however can be easily solved, by operating the system in mixed mode operation. In winters, the evaporative cooling fan can be turned off, which would make it work like scenario 2 – thus delivering 88% comfortable hours in the winter. This is also expected to reduce the energy consumption further as the evaporative cooler will not be used in the winter, thus increasing the 53.3% even further. Therefore, in this scenario, for the whole year analysis, the evaporative cooler is disabled to avoid overcooling, resulting in 86% occupant thermal comfort satisfaction over the year. In summary, **the wind-catcher plus evaporative cooler is a highly effective design to provide thermal comfort, that is predicted to drastically improve the indoor air quality in classrooms in Kuwait whilst reducing the energy use by at least 53.3%.**

6.2.4 Scenario 4:

This final scenario was implemented to see if any benefit could be derived from utilizing an AC system for backup cooling. This simulation was set up such that the AC system turned on as soon as the indoor air temperature increased beyond 27.5C – as this was cooling setpoint in the baseline A/C only cooling scenario. This resulted in highly uncomfortable conditions, with 86% of the time building occupants predicted to be uncomfortable. Looking at the PMV range (-3 to -0.5), the occupants are predicted to be highly overcooled. The reason for this overcooling is hypothesized as follows.

The increased air flow inside the classroom due to the wind-catcher results in lowering the thermal neutral comfort temperature of the classroom occupants. This is in line with the previous studies in hot climates, suggesting that an increase in approximately 0.5m/s air velocity results in lowering the indoor air temperature for thermal comfort by 1°C – 2°C (Indraganti *et al.*, 2014). However, the threshold for AC on/off switching was set at 27.5°C without consideration of this fact which may be the cause for the excessive cooling.

One solution to avoid the overcooling would be to control the AC systems on/off using thermal comfort control, such as Fanger's PMV instead of indoor air temperature. In this case, the cooling setpoint would be a dynamic variable depending on the air velocity, humidity and indoor air temperature among other parameters.

A positive aspect of this design was the improved air quality, mainly due to the increased natural ventilation due to the wind-catcher design. However, the energy use is the highest for this scenario, as electricity is used by not only the air-conditioner but also the evaporative cooling fan.

In summary, **this option resulted in improved air quality, as with the other windcatcher scenarios, but it also led to overcooling of building occupants at the cost of the highest energy use among the four options considered in this work.**

6.3 Assessment of project aim and limitations of the work

In Chapter 1 and 2, a clear aim for this project were identified. This section analysis the work presented in this thesis relevant to the primary research aim of this project, to ascertain what has been achieved and to inform future work. The primary aim of this research, following an extensive literature review is repeated below as follows:

"To develop a natural ventilation-based strategy/design for classrooms in the hot and dry climate of Kuwait, to provide satisfactory thermal comfort at improved indoor air quality in an energy efficient manner".

In view of this aim, Chapter 4 presented the modelling of the different scenarios considered in this work. The baseline scenario was validated against data collected from field work from the Kuwait school in question. Following this, Chapter 5 presented the results of each scenario in detail to clearly demonstrate the predicted performance of each scenario in terms of thermal comfort, energy use, indoor air quality and water consumption. Finally, the current Chapter 6 has analysed each scenario, clearly highlighting the benefits that could be achieved from employing the wind-catcher with evaporative cooling.

While it may be said that the primary aim of the work has been achieved, this is subject to the following limitations.

Applicable of the wind-catcher plus evaporative cooling is limited to very dry climates as in Kuwait, as humidity is the core issue to overcome when implementing evaporative cooling in buildings. Humidity is one of the environmental variables that impact thermal comfort assessment and can be a critical parameter when using evaporative cooling in medium-high humid climates.

Furthermore, the wind-catcher design presented in this thesis is based on previous studies found in the literature reviewed. The recommendations from relevant literature were used to develop the 3m in addition to the roof, rectangular cross section, single column with four inlets shape for the wind catcher. Variation in shape, positioning on the building, partitioning of the column, optimization of the wind-catcher height to minimize energy use and maximize thermal comfort and indoor air quality has not been done in this work. On the other hand, this work in this thesis provides a good platform for this kind of work to be performed that could lead to further improved design – as suggested the future works section in the following chapter.

In this work, limited capability of the DesignBuilder software with regards to CFD analysis was utilized. While the focus of this work was to understand macro indicator at the building level, in order to truly understand the variation in air flow at a zone level and comfort variation arising from it requires analysis using specialized CFD tools. However, considering the scope of this project, and that the school classroom was a simple cuboid –the DesignBuilder CFD capability was considered suitable for this work.

The following chapter presented the key findings, conclusions derived from this analysis and gives directions for future work building on the limitations of the work presented in the above paragraphs.

Chapter 7– Conclusions and future work

7.1 Key findings

In this thesis, a natural ventilation design based on ancient ideas applied in the middle east, the wind-catcher was assessed as a design that could provide thermal comfort within educational buildings in Kuwait, whilst reducing the cooling energy demand and indoor CO_2 levels. The wind catcher with evaporative cooling was found to be the best option that resulted in a reduction of energy use by 53.3% along with improved indoor air quality as the carbon dioxide levels dropped from 80% occupied hours above the 1100 ppm threshold stipulated by the ASHRAE 55 standard, to only 10%. Based on the reviewed literature, the simulated wind-catcher is 3 metres in height above the roof, with four inlets in the wind catcher and the windows at occupant height facilitate natural ventilation air flow through the classroom. The primary hypothesis of this study has been evaluated and verified that single sided ventilated classroom air velocity is effectively increased by the wind catcher, and along with the cooling effect of the evaporative cooler, the thermal comfort for the occupants and required velocity is achieved. The study established that the recommended strategy of the wind-catcher with evaporative cooling can successfully provide sufficient air flow within the building, with an average velocity of 0.78 m/s in the classroom. With regards to climatic conditions impacting indoor air velocity, the most noteworthy is external wind speed, with the orientation of the building having no effect, which is in agreement with literature (Allard, 1998, Olgyay, 2015, Szokolay, 2004 and Givoni, 1998).

7.2 Conclusions:

Based on the results and analysis presented in Chapters 5 and 6, the following conclusions are drawn:

1. Using only a split room cooling system with single sided window ventilation to provide thermal comfort in Kuwaiti classrooms leads to considerable discomfort and poor indoor air quality.
2. A complete natural ventilation-based wind-catcher delivers good thermal comfort in the wintertime, drastically reducing the need for building heating during the winter. However, in the summertime, the building occupants are highly uncomfortable (98% discomfort hours) due to high temperatures. This design however results in improved air quality.

3. The wind-catcher supplemented by the evaporative cooler results in highly comfortable conditions in the summer (2% hours of discomfort) accompanied by a drastic reduction in energy use and improvement in indoor air quality. However, the evaporative cooler overcools building occupants during winter. Therefore, it is concluded that the wind-catcher plus evaporative cooler should be operated in 'mixed-mode', where the evaporative cooler can be turned off in the winter.
4. There is dramatic overcooling when an AC system is operated in conjunction with the wind-catcher and evaporative cooler. This is attributed to a lower thermal neutral temperature due to increased air velocity in the building. It is concluded that AC backup system should be controlled not based on indoor air temperature, but rather thermal comfort indicator to prevent such overcooling. This would actually turn the AC on when it's most needed, i.e. the peak summer conditions.

7.3 Suggested future work:

Based on the previously presented conclusions and the limitations of this work presented in this thesis, the following future works are suggested:

1. The simulation work predicts massive improvements in all parameters for the wind-catcher plus evaporative cooler, over the typical air-conditioning only HVAC design. It should be noted that the computer model was (without the wind catcher element) validated against field data collected. However, a practical demonstration activity is suggested as future work. This would help highlight any unforeseen inefficiencies in the wind-catcher design while demonstrating the utility of this approach to buildings cooling in practice. In view of the dramatically improved indoor air quality, the application of this approach can extend to different building types such as shopping malls and hospitals. However, before such an activity can be attempted, a demonstration project is required - that is currently lacking in literature.
2. It is suggested to understand the health impacts of improved air quality within Kuwait climatic conditions to a greater depth. Overcooling and low air-change rates in air-conditioned buildings lead to different adverse health impact that has a social and economic cost. In future work, both these costs can also be quantified to gauge the actual benefit that could be achieved through implementing the wind-catcher based design.
3. From an analysis of the scenarios, it is clear that controlling either the evaporative cooling fan (scenario 3) or the backup AC system (scenario 4), results in substantial

overcooling and energy wastage. It is proposed in future work that these systems be controlled using thermal comfort indicators such as Fanger's PMV instead of indoor air temperatures. It is hypothesised that such an approach will lead to improved thermal comfort in addition to reduced energy use.

4. The sizing of the wind-catcher system in this work was based on recommendations from literature (Awbi et. al, 2013). However, this work can be extended to conduct an optimization of the wind-catcher design for the buildings considered, within the considered climates.
5. Considering 53.3% reduction in energy use by the wind-catcher system over air-conditioning, it is suggested as part of future work to analyse different building types, as they may result in a variation of the effectiveness of this HVAC design. For example, the cooling requirements and layouts of shopping malls, residential apartment buildings, and hospitals are different to that of the typical Kuwait school. In addition, the building occupancy profile, comfort requirements etc. also vary across the building's types. Therefore, it would be advantageous to analyse these different building types using computer simulation before attempting practical demonstration projects.
6. Review of thermal comfort indicators within the context of hot desert climates such as Kuwait (with prevailing mean temperature go beyond 34°C) highlighted the limited applicability of currently available international adaptive comfort models. It is clear that the widely used Fanger's PMV and PPD, and the ASHREA 55 adaptive thermal comfort model have limited applicability in the Kuwait context due to extreme summer temperatures, and indeed the wider Middle East climate, is evident and is therefore presented as an avenue for future research.

While this study is conducted in Kuwait, it should be noted that the results from this project are likely applicable to many of the GCC countries, as they have a similar climate and culture. As such, it is suggested here that this work should not be considered applicable to Kuwait only, but in fact the wider GCC countries as well.

Chapter 8 - References

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